

(12) **United States Patent**
Stark et al.

(10) **Patent No.:** **US 10,823,866 B2**
(45) **Date of Patent:** **Nov. 3, 2020**

(54) **ARRAYED DISTRIBUTED ACOUSTIC SENSING USING SINGLE-PHOTON DETECTORS**

(58) **Field of Classification Search**
CPC G01V 1/226; E21B 47/017
(Continued)

(71) Applicant: **Halliburton Energy Services, Inc.**,
Houston, TX (US)

(56) **References Cited**

(72) Inventors: **Daniel Joshua Stark**, Houston, TX
(US); **John L. Maida**, Houston, TX
(US); **Casey Giron**, Danville, CA (US);
David Andrew Barfoot, Houston, TX
(US)

U.S. PATENT DOCUMENTS

7,049,593 B2 5/2006 Sobolewski et al.
7,844,188 B2 11/2010 Takemoto
(Continued)

(73) Assignee: **Halliburton Energy Services, Inc.**,
Houston, TX (US)

OTHER PUBLICATIONS

(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 141 days.

Balanced Amplified Photodetectors with Fast Monitor Output.
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=5201.

(Continued)

(21) Appl. No.: **16/098,166**

Primary Examiner — Tarun Sinha

(22) PCT Filed: **Aug. 26, 2016**

(74) *Attorney, Agent, or Firm* — Haynes and Boone, LLP

(86) PCT No.: **PCT/US2016/049021**
§ 371 (c)(1),
(2) Date: **Nov. 1, 2018**

(57) **ABSTRACT**

(87) PCT Pub. No.: **WO2018/038739**
PCT Pub. Date: **Mar. 1, 2018**

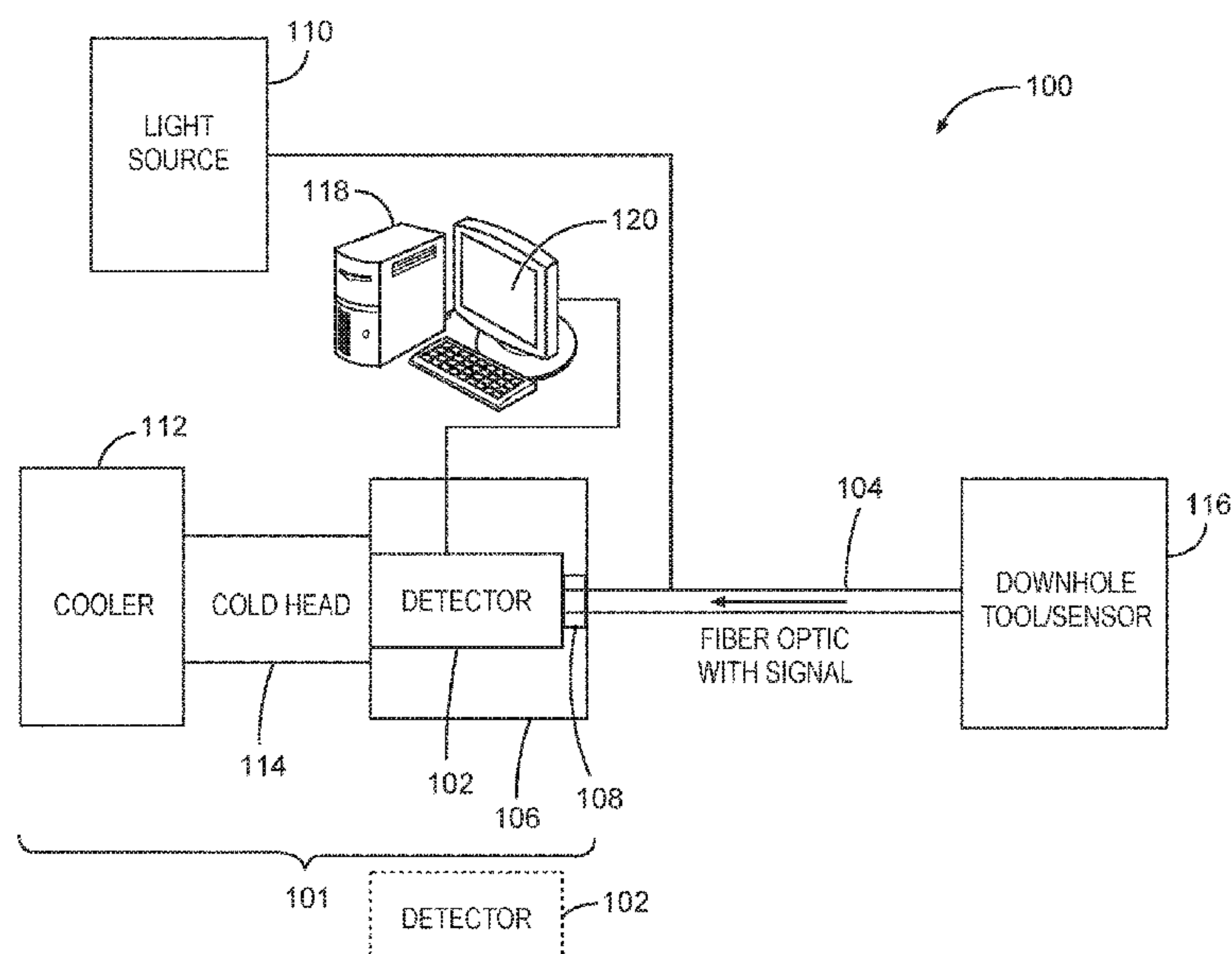
In some embodiments, a method and apparatus, as well as an article, may operate to determine downhole properties based on detected optical signals. An optical detection system can include a fiber optic cable having a sensing location to generate a backscattered Rayleigh signal representative of measurement parameters. The optical detection system can further include a light source to transmit a measurement signal to cause the sensing location to provide the backscattered Rayleigh signal. The optical detection system can further include an optical detector comprising a single-photon detector (SPD) for detecting the backscattered Rayleigh signal received over the fiber optic cable. The optical detection system can further include circuitry to produce an acoustic signal representative of a downhole property based on the phase of the backscattered Rayleigh signal. Additional apparatuses, systems, and methods are disclosed.

(65) **Prior Publication Data**
US 2019/0146107 A1 May 16, 2019

(51) **Int. Cl.**
G01V 1/22 (2006.01)
E21B 47/017 (2012.01)

(52) **U.S. Cl.**
CPC **G01V 1/226** (2013.01); **E21B 47/017**
(2020.05)

18 Claims, 16 Drawing Sheets



(58) Field of Classification Search

USPC 73/152.58
See application file for complete search history.

OTHER PUBLICATIONS

(56) References Cited

U.S. PATENT DOCUMENTS

8,294,103	B2	10/2012	Gibbons et al.	
2005/0011199	A1	1/2005	Grisham et al.	
2006/0023885	A1 *	2/2006	Trifonov	H04L 9/0858 380/256
2007/0013911	A1 *	1/2007	DiFoggio	G01J 3/26 356/436
2012/0063789	A1	3/2012	Yuan et al.	
2013/0087689	A1	4/2013	Woodward et al.	
2014/0087952	A1	3/2014	Nam et al.	
2014/0153926	A1	6/2014	Mower et al.	
2014/0299751	A1	10/2014	Tang et al.	
2015/0114127	A1 *	4/2015	Barfoot	G01H 9/004 73/655
2016/0168980	A1	6/2016	Bedry et al.	

Dauler et al. "High-Efficiency, Multi-Element Single-Photon Detectors." SPIE Newsroom. Oct. 28, 2013.

International Search Report and The Written Opinion of the International Search Authority, or the Declaration, dated May 26, 2017, PCT/US2016/049021, 13 pages, ISA/KR.

Marsili et al. "Detecting Single Infrared Photons with 93% System Efficiency." *Nature Photonics*, vol. 7. pp. 210-214. Feb. 24, 2013.

Spina et al. "Microengineered CH₃ NH₃ PbI₃ Nanowire/Graphene Phototransistor for Low-Intensity Light Detection at Room Temperature." *Small*. vol. 11, Issue 37. pp. 4824-4828. Oct. 7, 2015.

Verma et al. "A Four-Pixel Single-Photon Pulse-Position Array Fabricated from WSi Superconducting Nanowire Single-Photon Detectors." *Applied Physics Letters*. vol. 104, Issue 5. Nov. 2013.

Wang et al. "Silicon Photonic Integrated Circuit Swept-Source Optical Coherence Tomography Receiver With Dual Polarization, Dual Balanced, In-Phase and Quadrature Detection." *Biomedical Optics Express*. vol. 6, Issue 7. pp. 2562-2574. Jun. 17, 2015.

Zhao et al. "Unbounded High Dynamic Range Photography using a Modulo Camera." *MIT Media Lab, MIT Lincoln Lab, Singapore University of Technology and Design*. www.mit.edu/~hangzhao/papers/moduloUHDR.pdf.

* cited by examiner

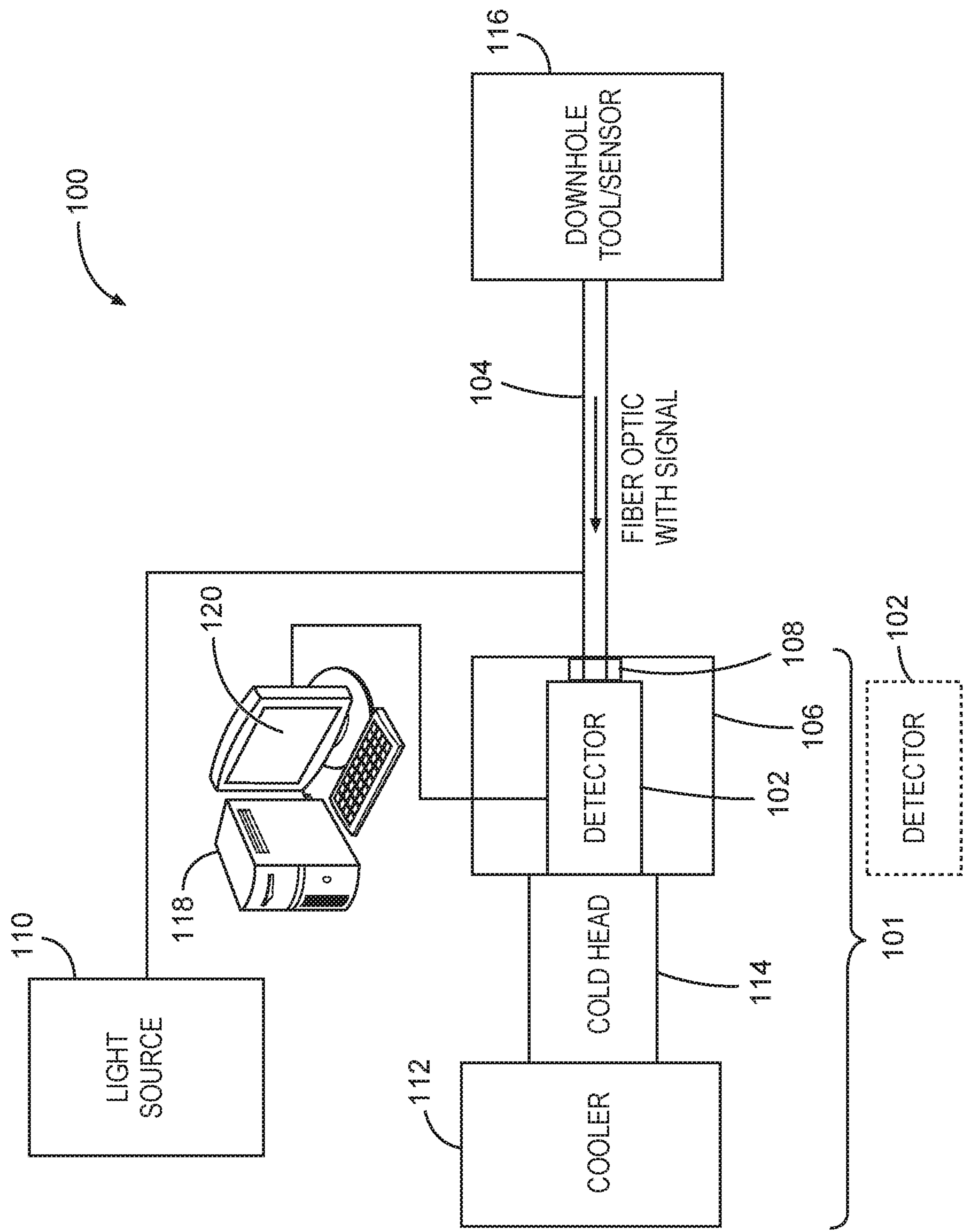


FIG. 1

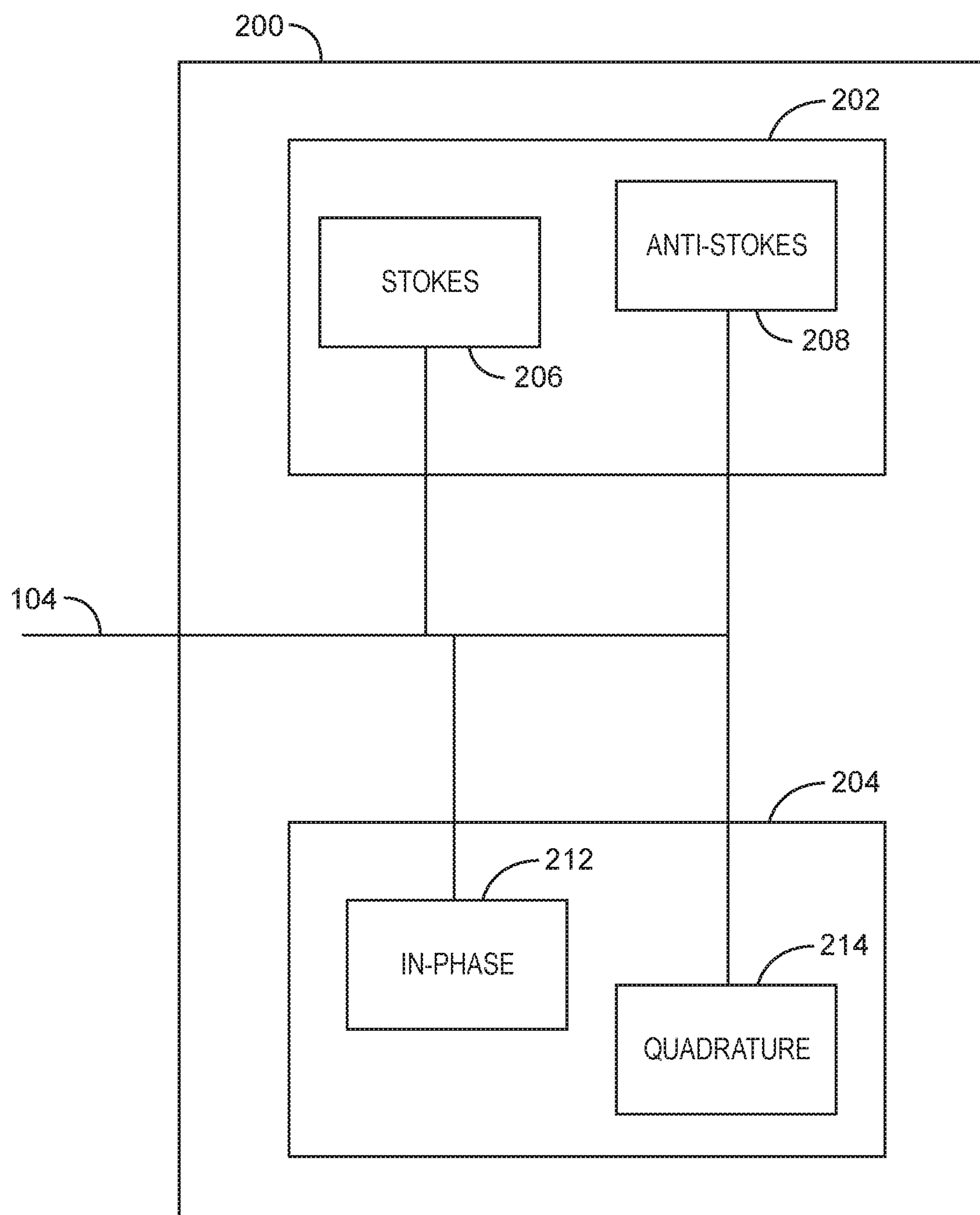


FIG. 2

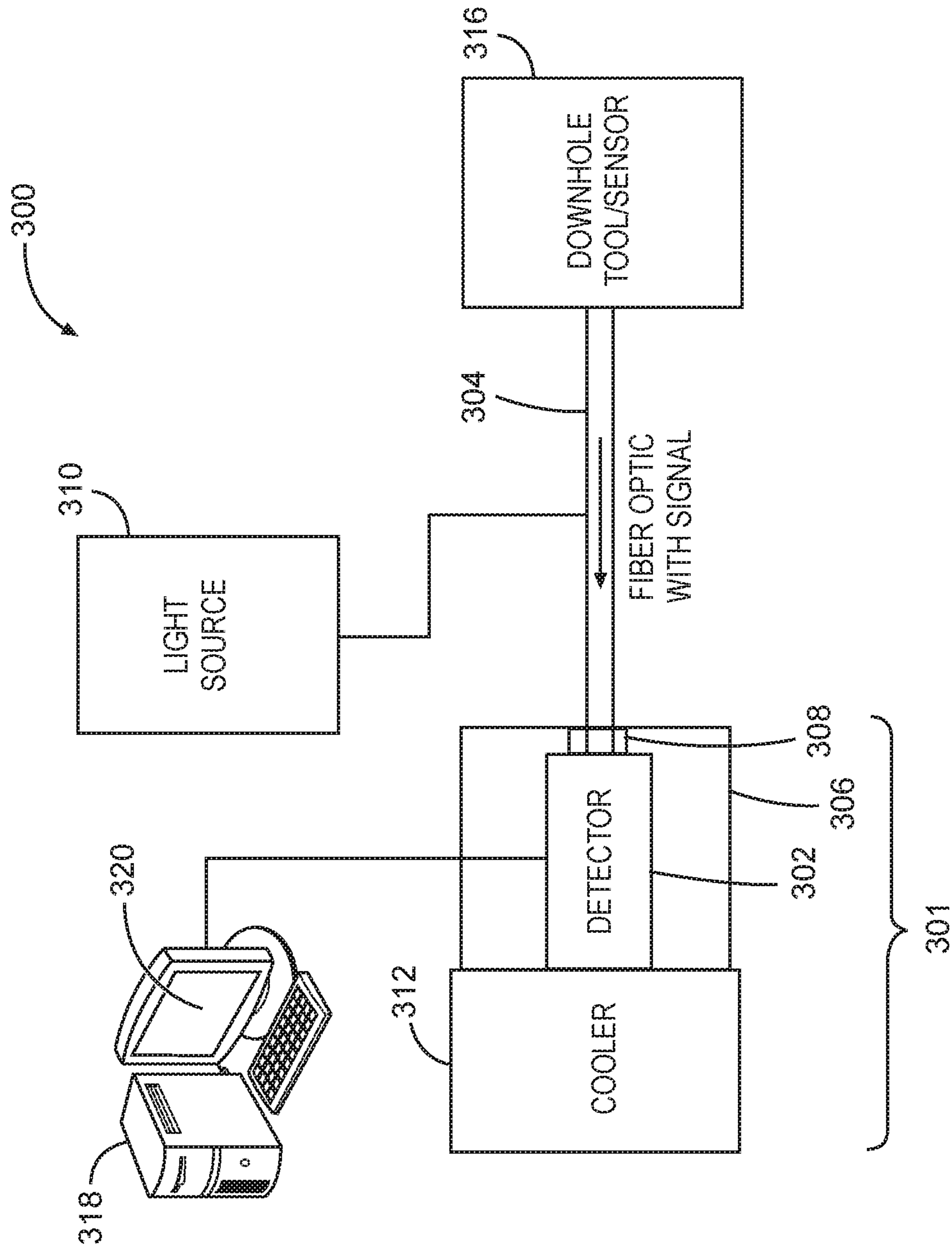


FIG. 3

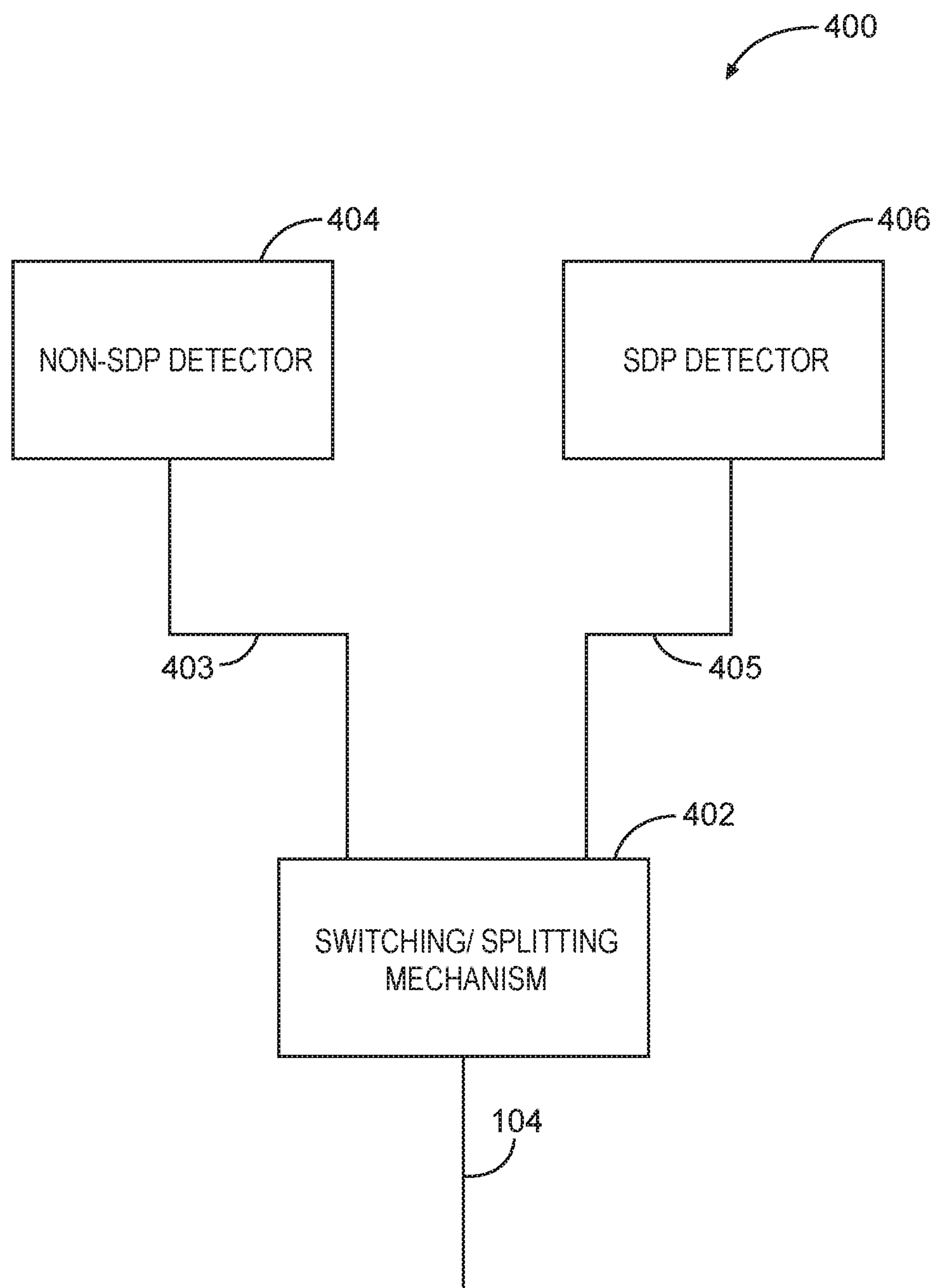


FIG. 4

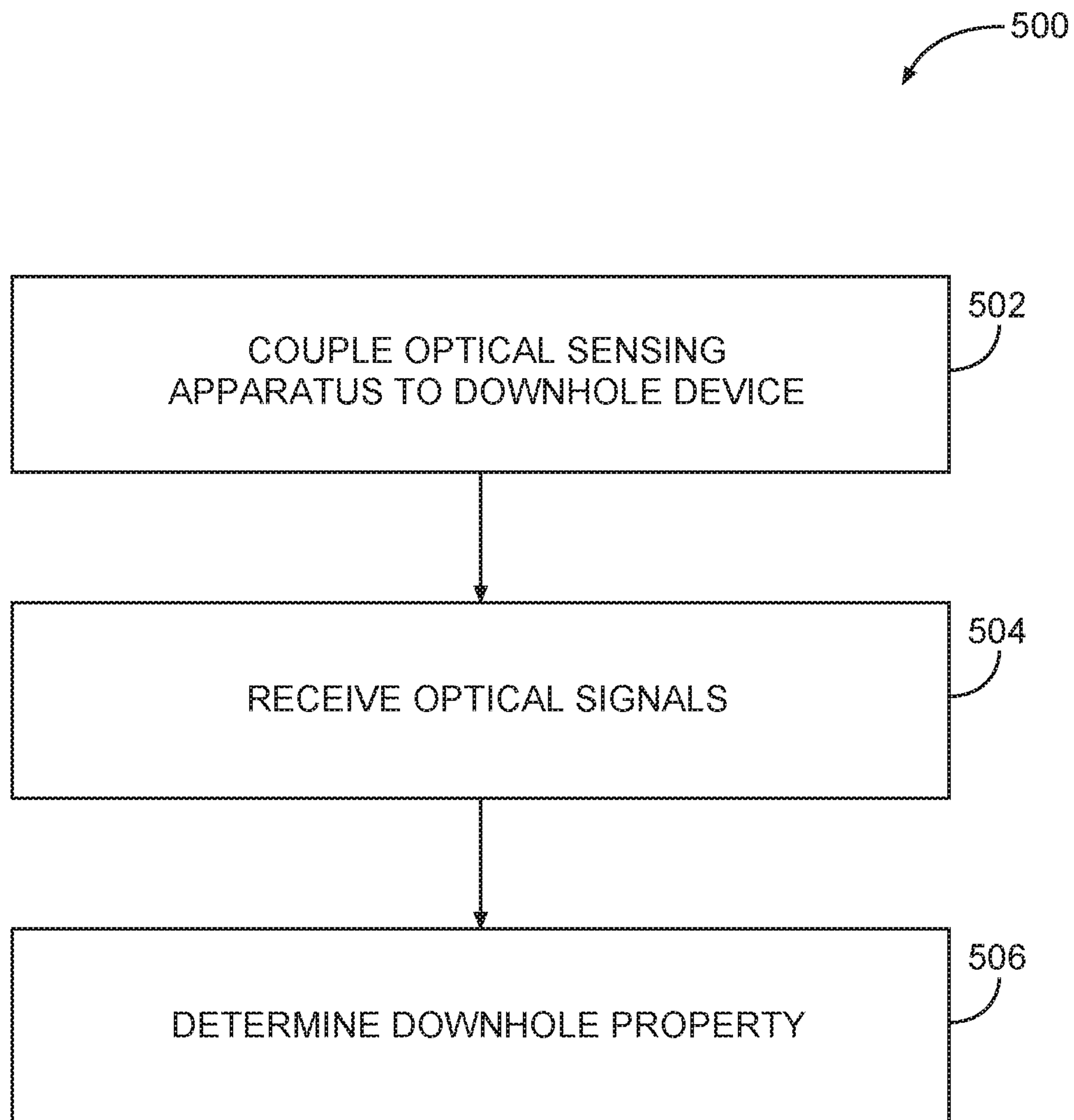


FIG. 5

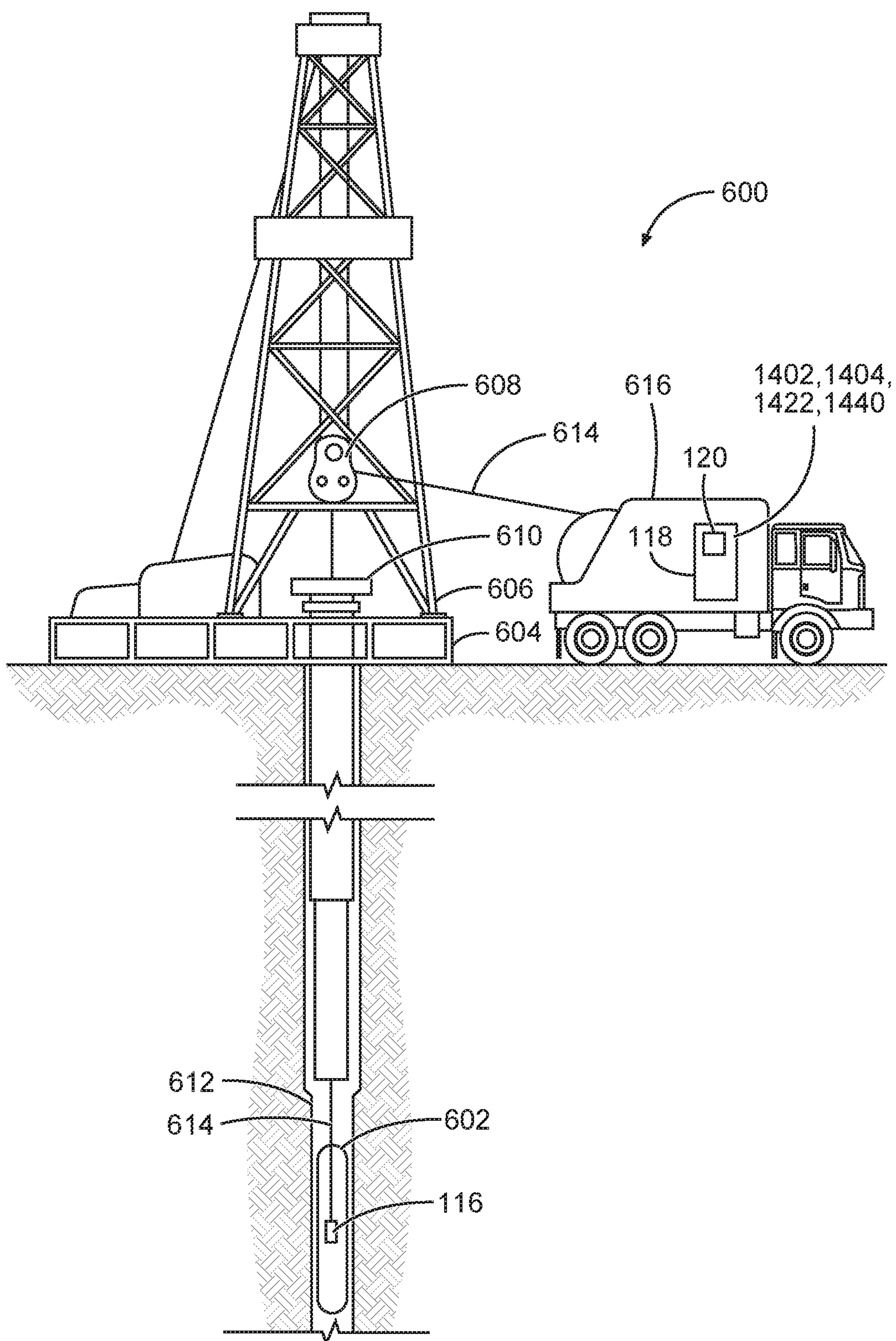


FIG. 6

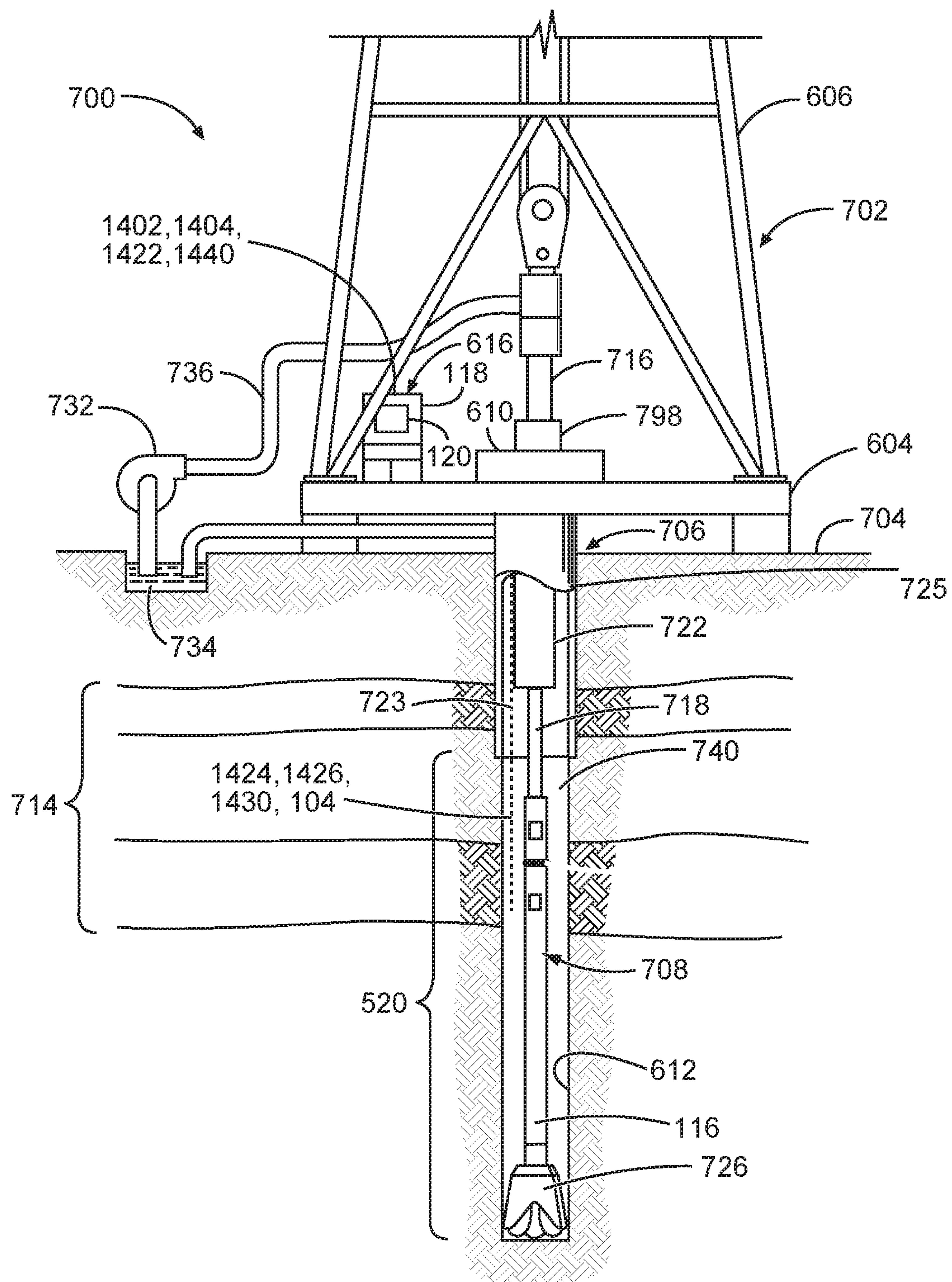


FIG. 7

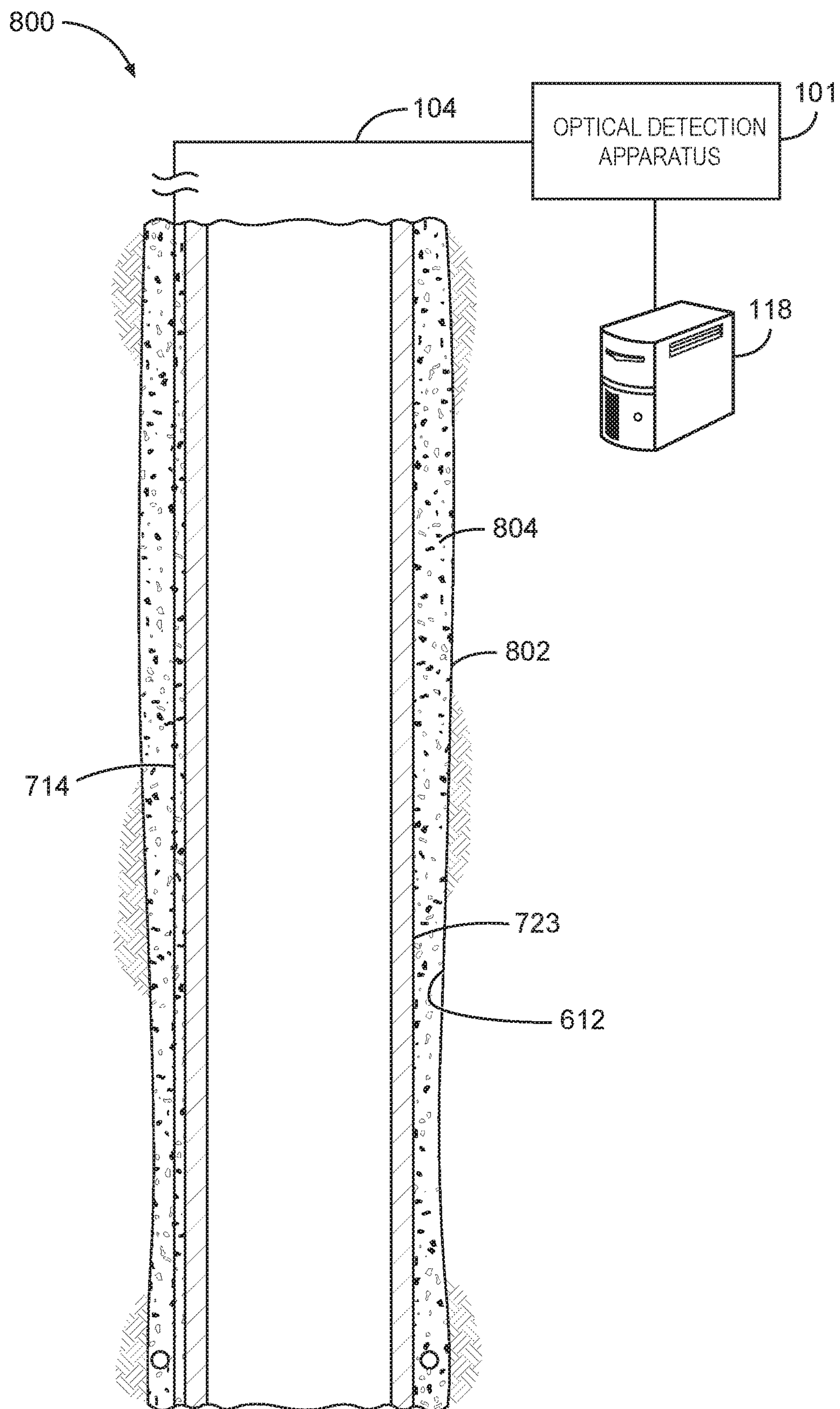


FIG. 8

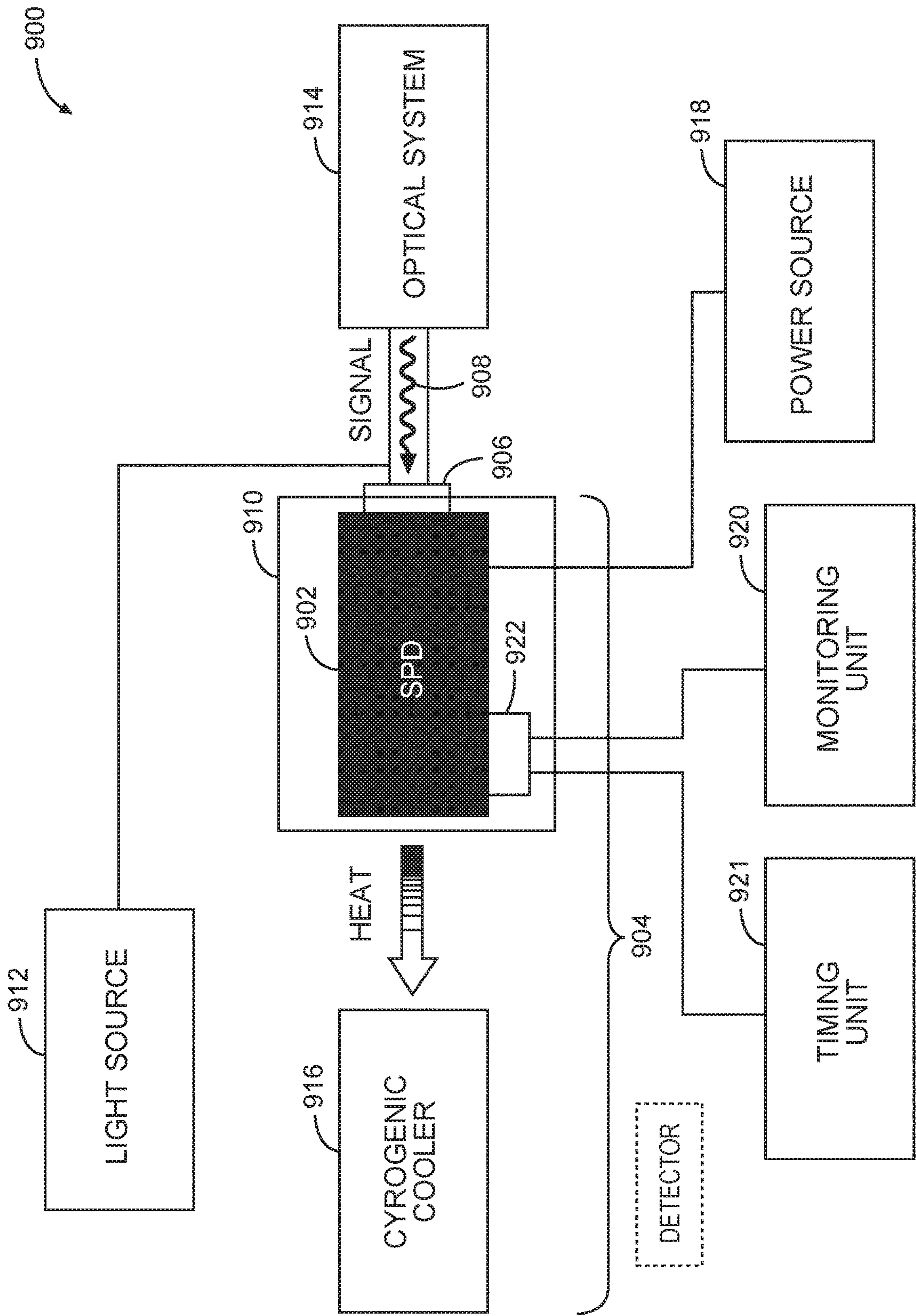


FIG. 9

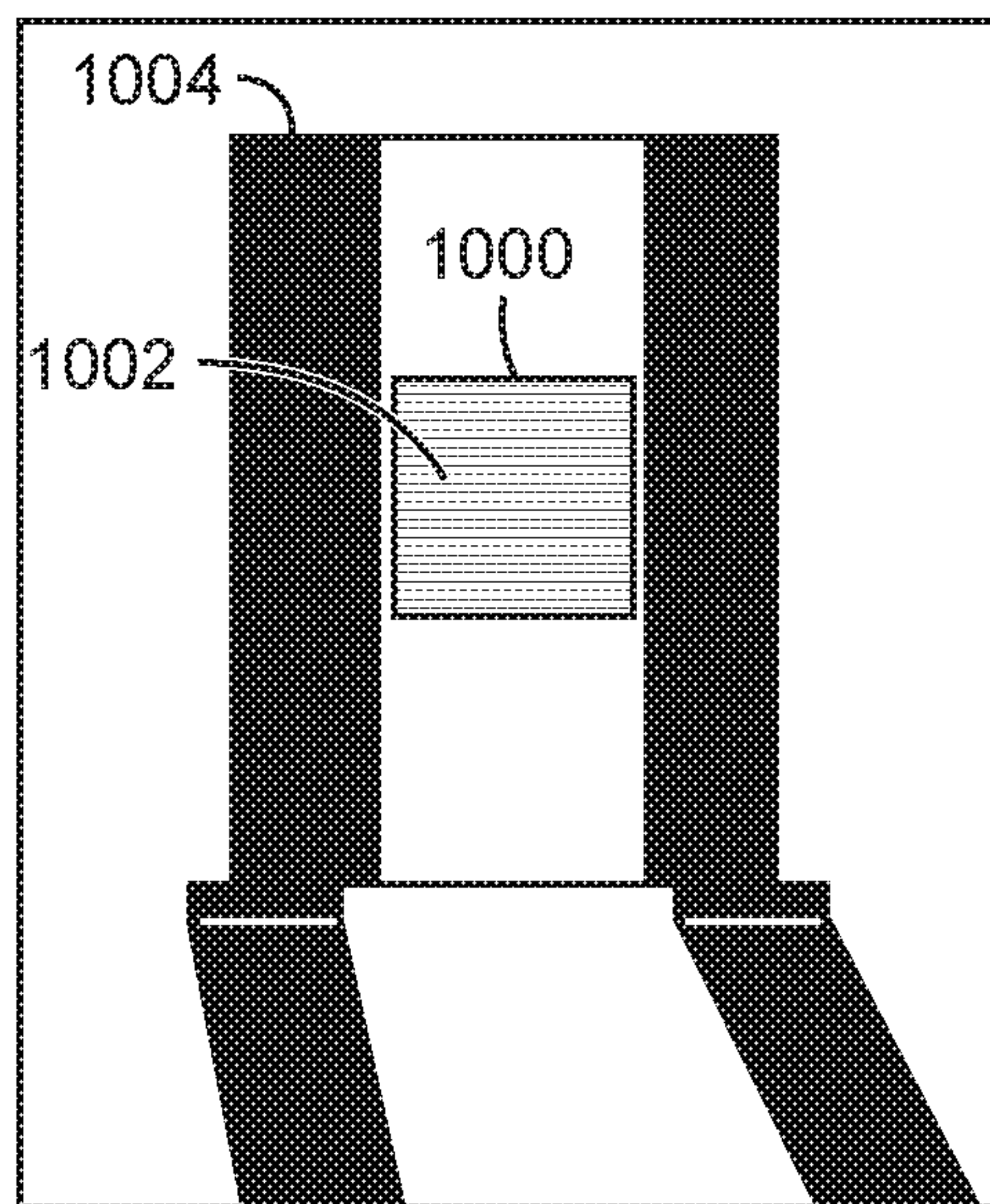


FIG. 10A

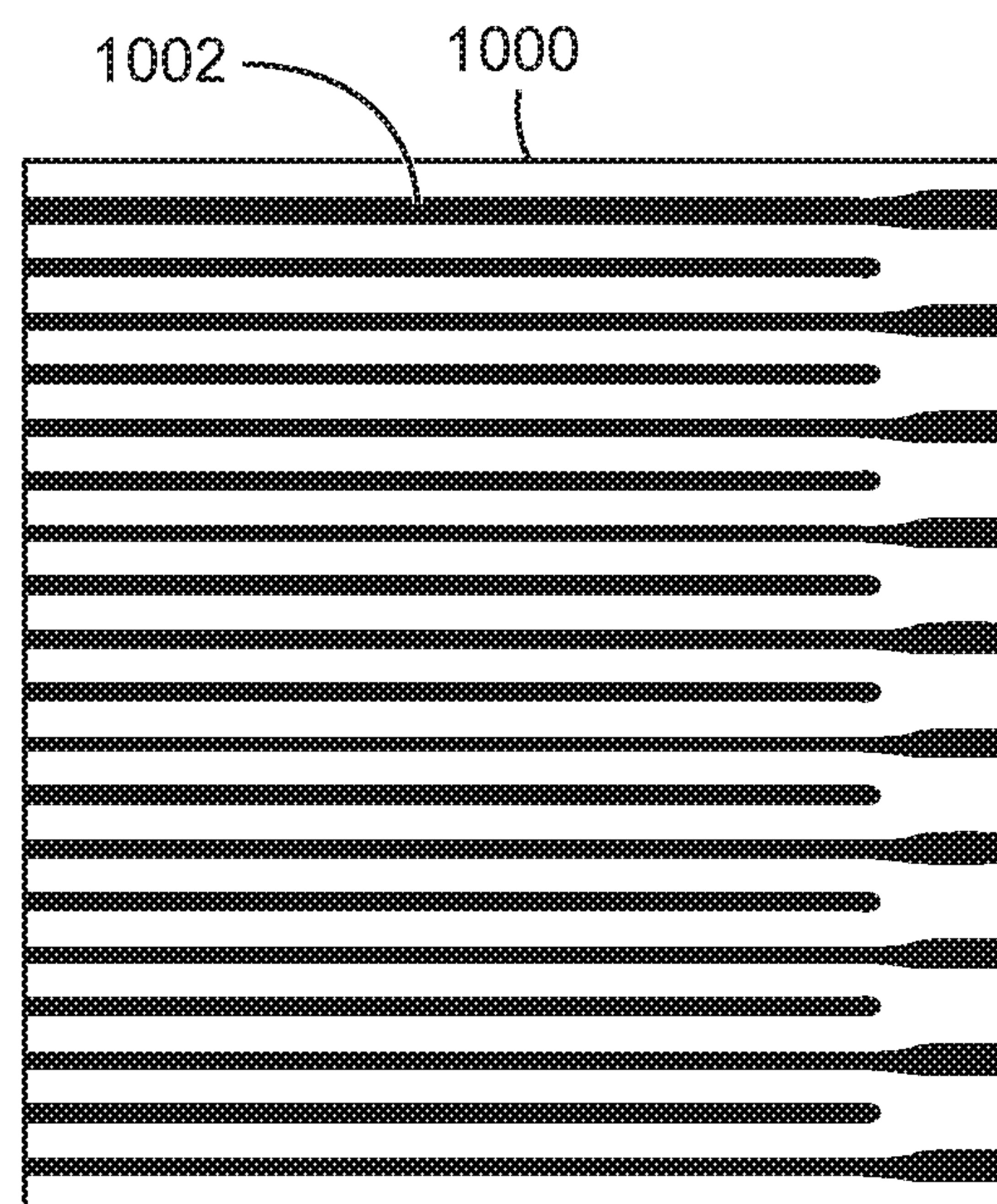


FIG. 10B

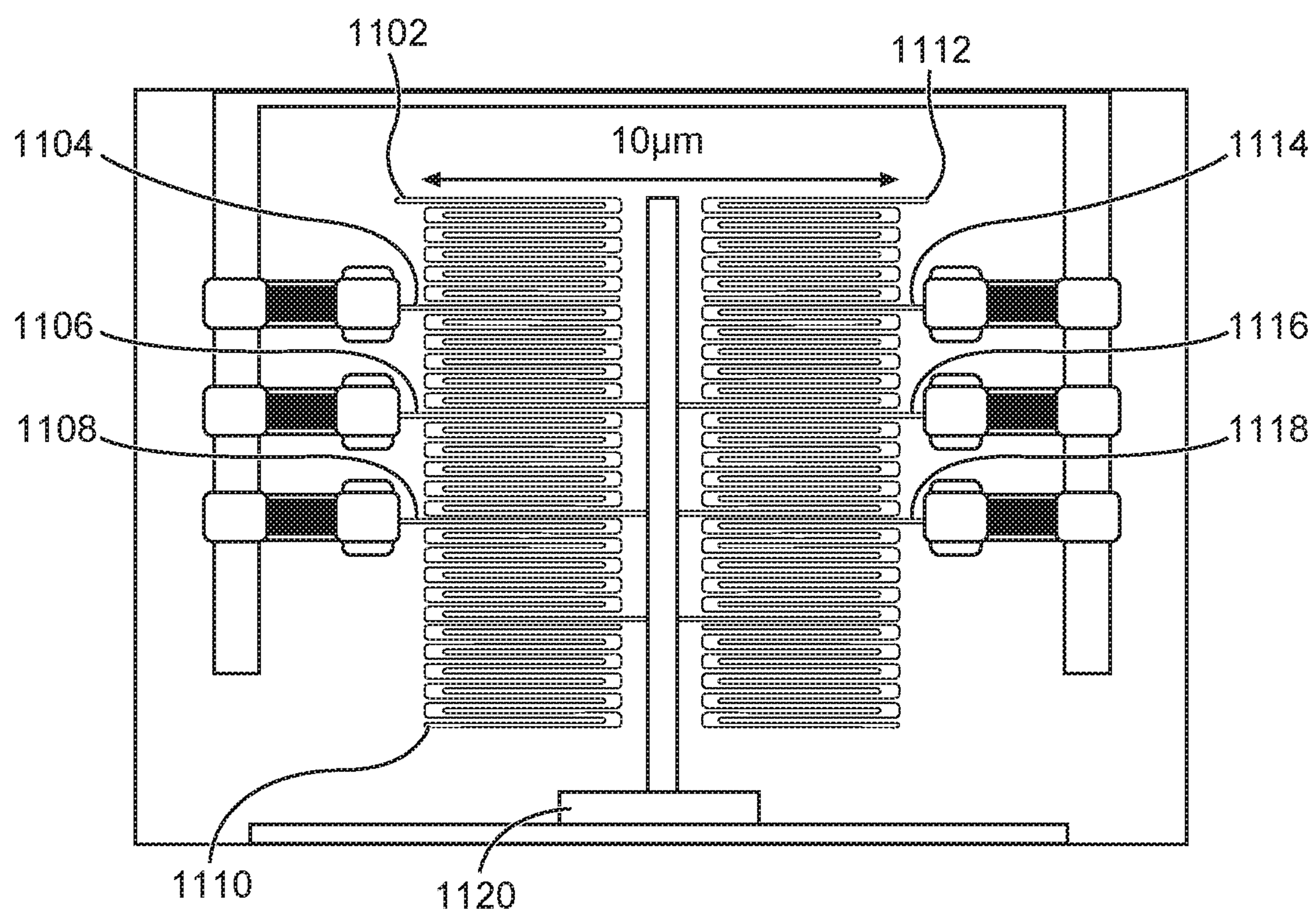


FIG. 11

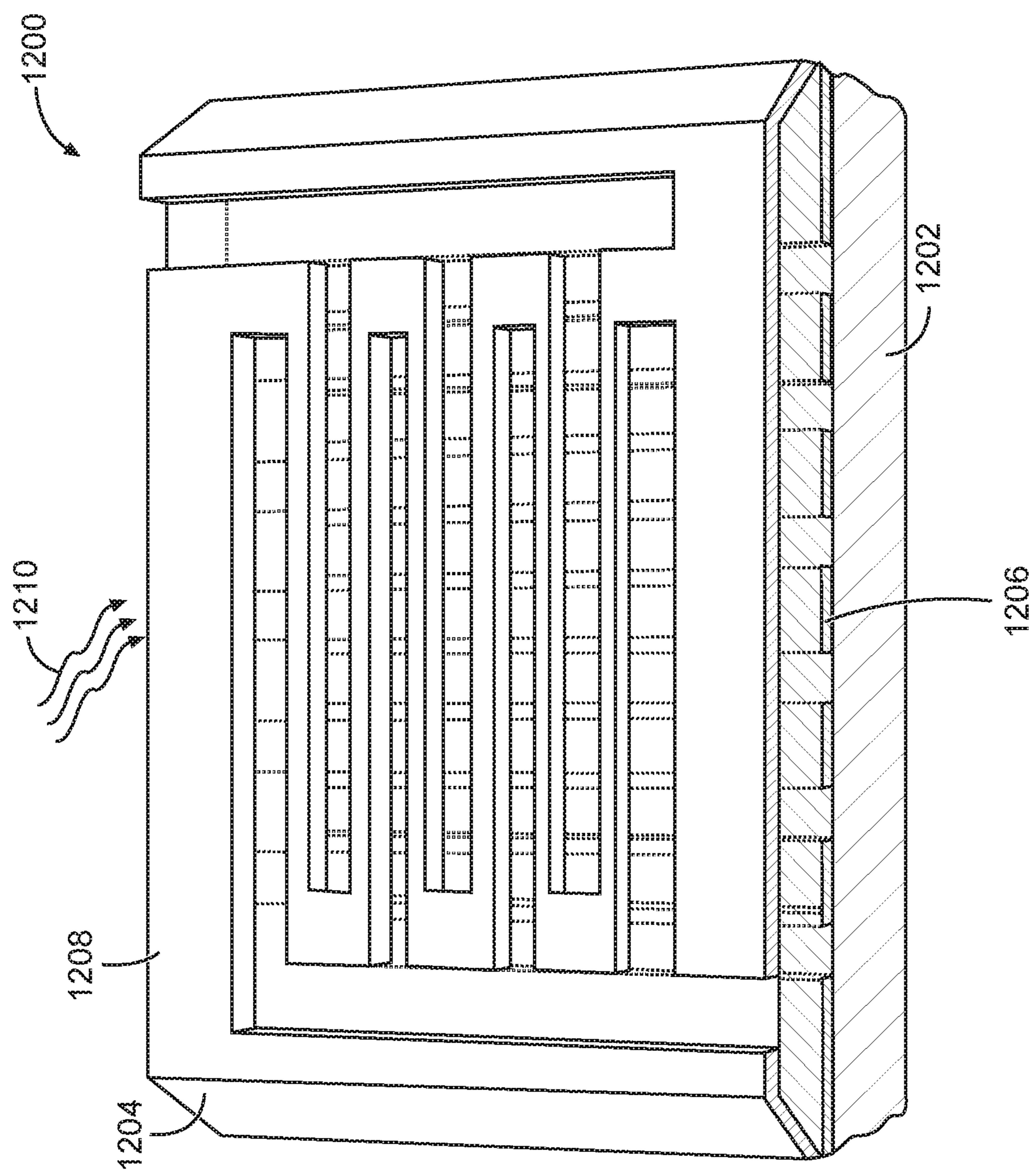


FIG. 12

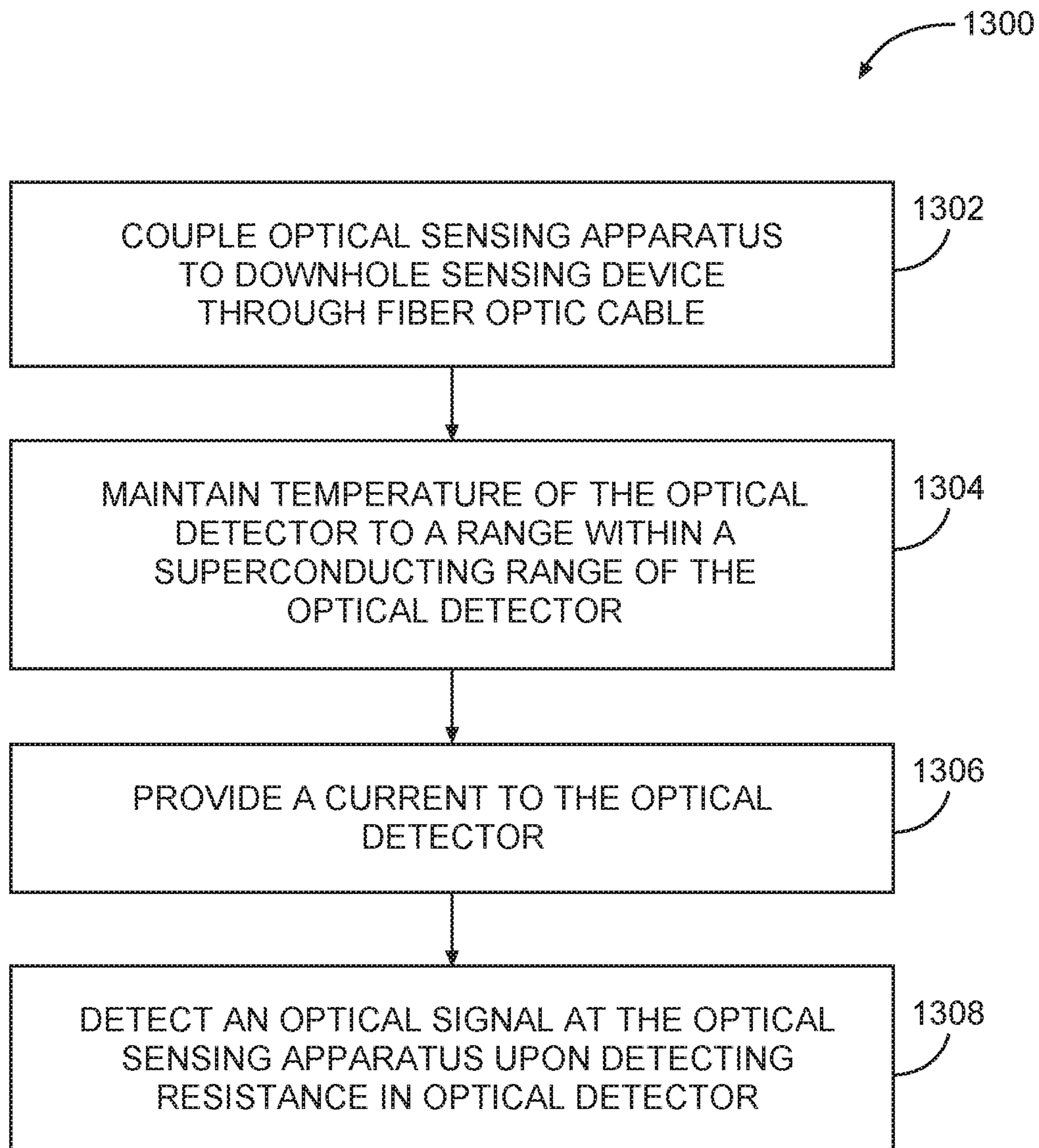
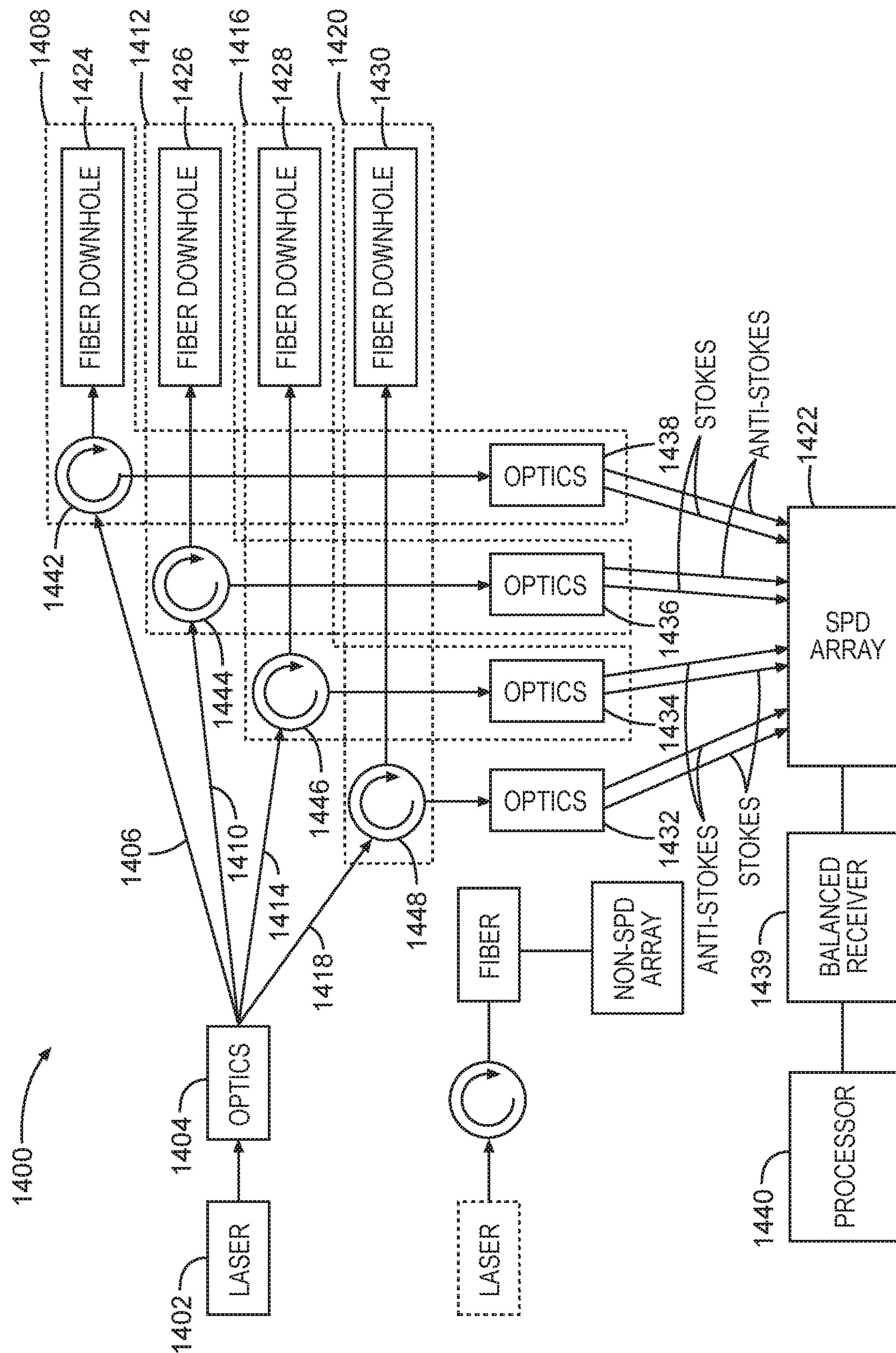


FIG. 13



ॐ

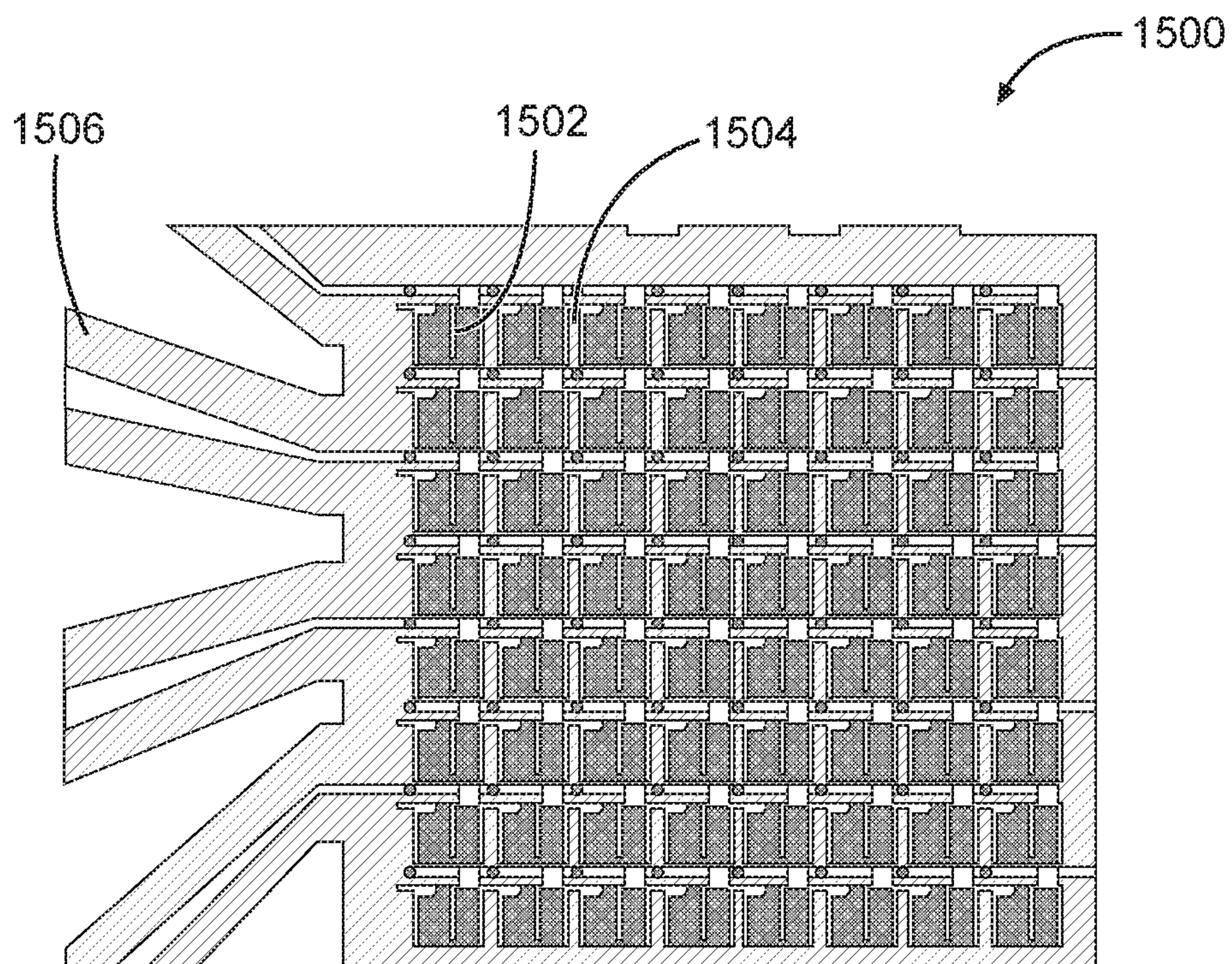


FIG. 15A

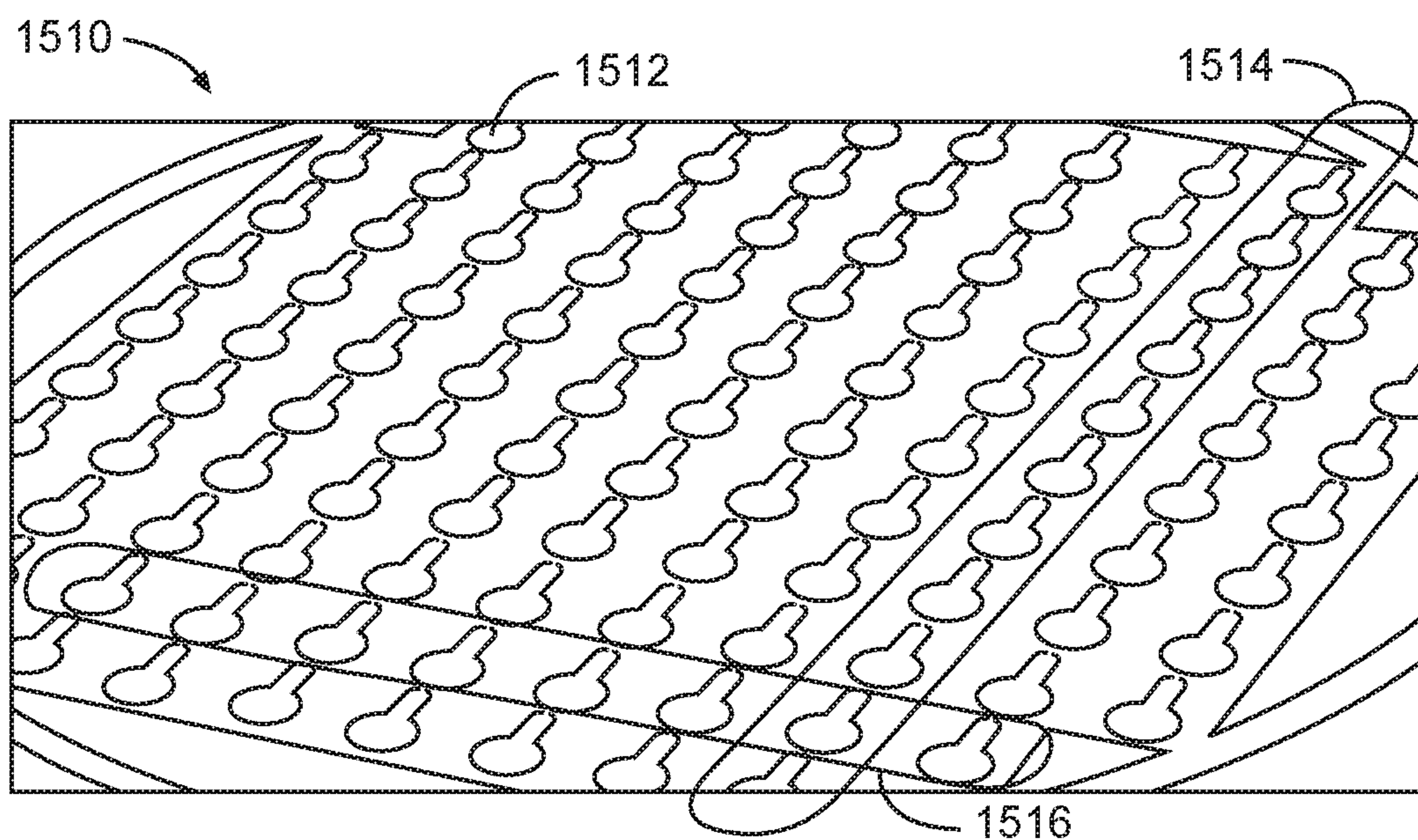
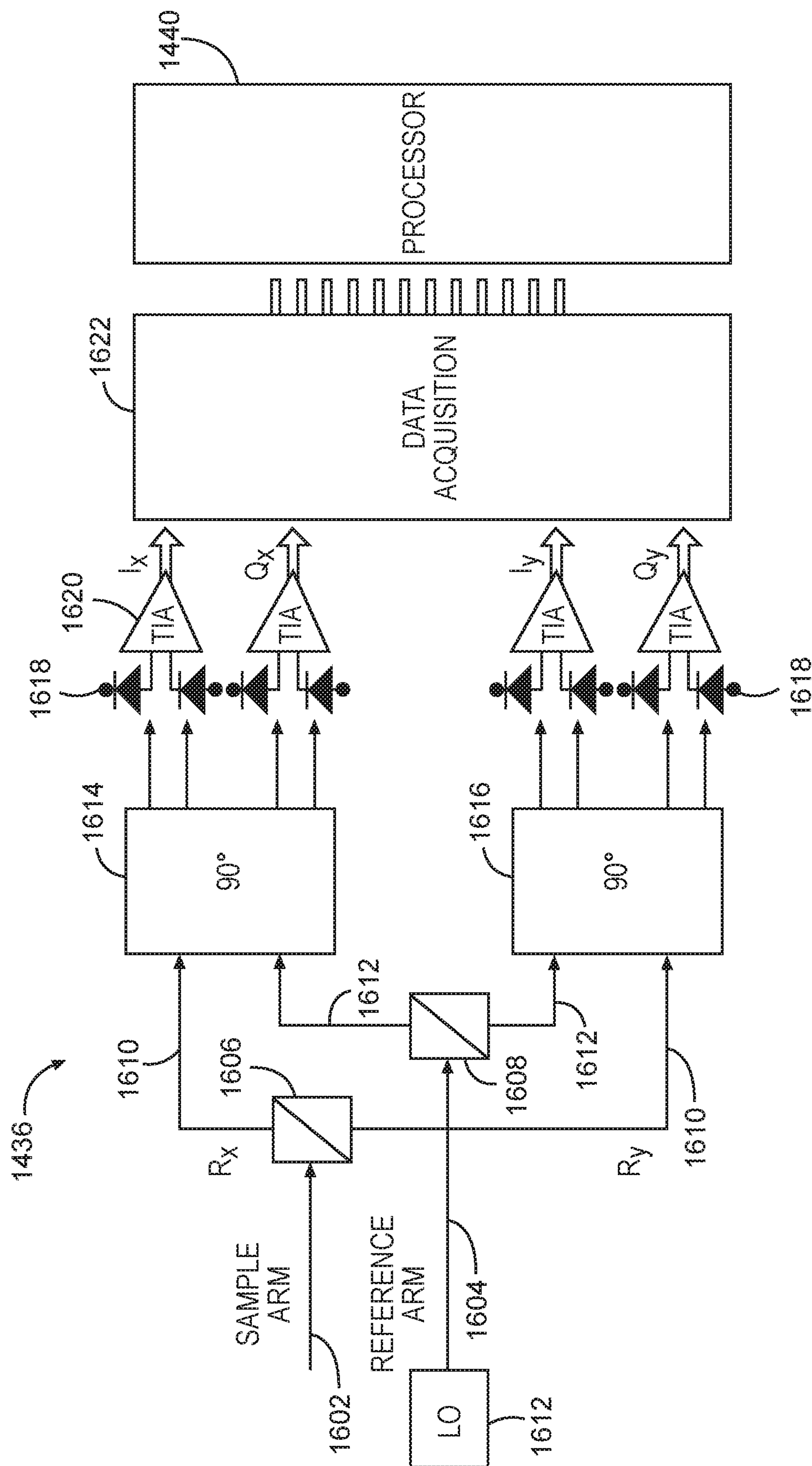


FIG. 15B



91

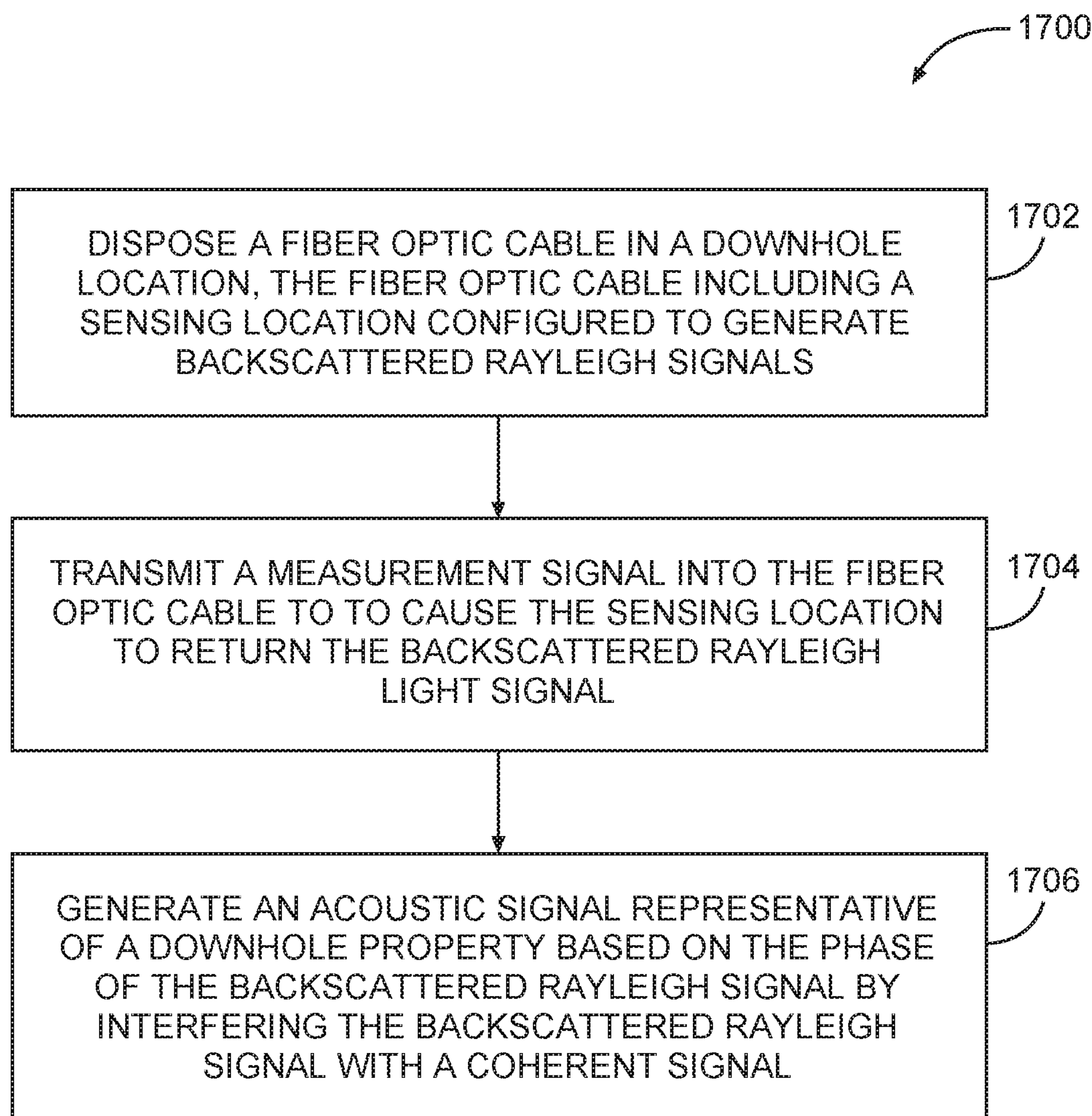


FIG. 17

ARRAYED DISTRIBUTED ACOUSTIC SENSING USING SINGLE-PHOTON DETECTORS

PRIORITY

The present application is a U.S. National Stage patent application of International Patent Application No. PCT/US2016/049021, filed on Aug. 26, 2016, the benefit of which is claimed and the disclosure of which is incorporated herein by reference in its entirety.

BACKGROUND

Understanding the structure and properties of geological formations can reduce the cost of drilling wells for oil and gas exploration. Measurements made in a borehole (i.e., downhole measurements) are typically performed to attain this understanding, to identify the composition and distribution of material that surrounds the measurement device downhole. Optical detectors are often used to perform these measurements. Optical detectors use fiber optic cables that have greater temperature capability, corrosion resistance and electromagnetic insensitivity as compared to some other types of energy conductors, such as wires or cables. However, optical detectors are still subject to various noise sources that can reduce accuracy and reliability of measurements taken with optical detectors.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of an optical detection system including an optical detector and a cooling system including a cold head for cooling the optical detector in accordance with various embodiments.

FIG. 2 is a block diagram of a single integrated optical chip including a group of optical detectors dedicated to distributed temperature sensing (DTS) and another group dedicated to distributed acoustic sensing (DAS) in accordance with various embodiments.

FIG. 3 is a block diagram of an optical detection system including an optical detector and a cooling system, without an intervening cold head, for cooling the optical detector in accordance with various embodiments.

FIG. 4 is a block diagram of an optical detection system including a switching mechanism to direct optical signals to an optical detector in accordance with various embodiments.

FIG. 5 is a flow chart of an example method of optical sensing in accordance with some embodiments.

FIG. 6 is a diagram of a wireline system embodiment.

FIG. 7 is a diagram of a drilling rig system embodiment.

FIG. 8 is a diagram of a permanent monitoring system embodiment.

FIG. 9 is a block diagram of an optical detection system including a superconducting nanowire single-photon detector (SNSPD) in accordance with various embodiments.

FIG. 10A illustrates an SNSPD using meandering nanowires in accordance with various embodiments.

FIG. 10B illustrates an enlarged view of a superconductive portion of the SNSPD of FIG. 10A.

FIG. 11 illustrates an SNSPD having parallel pixels in accordance with various embodiments.

FIG. 12 illustrates a multilayer SNSPD structure in accordance with various embodiments.

FIG. 13 is a flow chart of an example method of optical sensing with an SNSPD optical detector in accordance with various embodiments.

FIG. 14 is a block diagram of an arrayed DAS system in accordance with various embodiments.

FIG. 15A illustrates an SPD array for fiber imaging in accordance with various embodiments.

FIG. 15B illustrates a grid of SPD arrays in accordance with various embodiments.

FIG. 16 is a block diagram of a balanced receiver for retrieving phase information from a backscattered Rayleigh signal in accordance with various embodiments.

FIG. 17 is a flow chart of an example method of estimating a downhole parameter in accordance with various embodiments.

DETAILED DESCRIPTION

Noise sources interfere with downhole measurement systems and can cause deterioration in signal-to-noise ratios (SNRs) of measurement signals. Thus, ongoing efforts are directed to reducing noise to improve signal-to-noise ratios in optical detection systems. For example, SNR can be increased by modifying certain parameters (e.g., resolution, fiber depth, and repetition rate). However, modification of these parameters can reduce the accuracy of the optical detection system. To address these concerns and others, systems, apparatuses, and methods described herein provide for cooling optical detectors to ultra-low temperatures (e.g., below 210 degrees Kelvin, below 70 degrees Kelvin or, in some embodiments, below 4 degrees Kelvin). This cooling can reduce or effectively eliminate thermal noise, thereby raising measurement signal SNRs without changing other parameters, in optical sensors for optical sensing.

FIG. 1 is a block diagram of an optical detection system 100. An optical detection apparatus 101 of the optical detection system 100 includes an optical detector 102 for detecting light received through a fiber optic cable 104. In some embodiments, the light includes wavelengths in a visible range of wavelengths. However, embodiments are not limited thereto and the light can include wavelengths in an infrared range of wavelengths and/or in an ultraviolet range of wavelengths.

In some embodiments, the optical detector 102 includes a low-light detector (LLD) or an extremely low-light detector (ELLD). In some embodiments, the optical detector 102 includes a single-photon detector (SPD). In some embodiments, the optical detector 102 includes an avalanche photodiode. In some embodiments, the optical detector 102 includes carbon nanotubes or other nano structures. However, embodiments are not limited to these example optical detectors and other types of optical detectors can be used. For example, the optical detector 102 can include an integrated optical chip such as a silicon photonic resonator or a focal planar array detector, among other optical detector types.

In some embodiments, the integrated optical chip can support multiple SPDs with each detector (or group of detectors) dedicated to a specific sensing type. For example, as shown in FIG. 2, a single integrated chip 200 can include a group of optical detectors 202 dedicated to distributed temperature sensing (DTS) and another group 204 dedicated to distributed acoustic sensing (DAS). The DTS group can be further split into sub-groups of optical detectors that can sense scattered light (as opposed to incident light) components, including one group 208 of optical detectors for sensing an anti-Stokes signal and another group 206 of optical detectors for sensing the Stokes signal of scattered light. Likewise, the DAS group can be split into a set 212 of optical detectors that sense one interferometric output (the

in-phase) and a set **214** that detects the other output (e.g., the quadrature). Other systems can be provided such as distributed strain sensing (DSS) systems. In some embodiments, the optical detector **102** can include additional optical elements to improve signal to noise ratios. These additional optical elements can include lenses, filters, mirrors, mixers, wavelength demultiplexers, and other elements.

Referring again to FIG. 1, the optical detection apparatus **101** can include a housing **106** for enclosing the optical detector **102** and for providing an optical shield for the optical detector **102**. The housing **106** can include an aperture **108** for passage of the fiber optic cable **104**. However, embodiments are not limited thereto, and in some embodiments, a coupler can be mounted so that the fiber optic cable **104** terminates at a boundary of the housing **106**. The optical detection system **100** includes a light source **110**, separate from the optical detector **102** and the housing **106**, for providing (e.g., “transmitting”) light through the fiber optic cable **104**. In some embodiments, the light source **110** can provide light through one fiber optic cable **104** and light can be received by the optical detector **102** on a separate fiber optic cable **104**, although embodiments are not limited to any particular number of fiber optic cables **104** or combinations thereof. In some embodiments, the light source **110** can include additional optical components configured to provide or delivery the appropriate light to the system including filters, mixers, non-linear crystals, timing chips, wavelength multiplexers, etc. In some embodiments, the light source **110** can be downhole and in some embodiments, the light source **110** can be on the surface. In some embodiments, multiple light sources can be provided on the surface, downhole, or a combination thereof.

The optical detection apparatus **101** includes a cooling mechanism **112** having the housing **106** mounted thereto. The cooling mechanism **112** is configured to maintain the temperature of a light-sensitive region of the optical detector **102** within a temperature range below 210 degrees Kelvin. In some embodiments, the cooling mechanism **112** operates using liquid helium (He) or liquid nitrogen (N₂). In some embodiments, the cooling mechanism **112** maintains the temperature of the light-sensitive region of the optical detector **102** at a temperature at or below 80 degrees Kelvin. In some embodiments, the cooling mechanism **112** maintains the temperature of the light-sensitive region of the optical detector **102** at a temperature at or below 5 degrees Kelvin (e.g., when sealed helium systems are used). In some embodiments, the cooling mechanism **112** can be of one or more of a variety of configurations, including Dilution-Magnetic, Collins-Helium Liquefier, Joule-Thomson, Stirling-cycle cryocooler, self-regulated Joule-Thomson, Closed-Cycle Split-Type Stirling, Pulse Tube, a two-stage Gifford-McMahon cryogenic cooler or multi-stage Gifford-McMahon cryogenic cooler, or a cooler using magnetocaloric effect, by way of example. Lowering the temperature of the optical detector **102** improves the SNR of the optical detector **102** by decreasing dark current, by increasing sensitivity, and by reducing resistive loss by causing the optical detector **102** to enter a superconducting regime of operation. In some embodiments or configurations non-SPD optical detectors **102** will not enter a superconducting regime, while still having little to no thermal noise.

In some embodiments, the optical detection apparatus **101** includes a cold head **114** between the optical detector **102** and the cooling mechanism **112**. However, some embodiments do not include a cold head **114**. FIG. 3 is a block diagram of an optical detection system **300** including an optical detector **302** and a cooling mechanism **312**, without

an intervening cold head, for cooling the optical detector **302** in accordance with various embodiments. As with the optical detection system **100**, the optical detection system **300** includes a light source **310**, and a fiber optic cable **304** coupled between the downhole unit **316** and the optical detector **302**. The optical detector **102** can be encased in a housing **306** with or without an aperture **308** for permitting passage of the fiber optic cable **304**.

Referring again to FIG. 1, in some embodiments, the housing **106** is mounted to the cooling mechanism **112** such that moisture is prevented from entering the housing. For example, the housing **106** can be mounted such that a vacuum seal is formed with the cooling mechanism **112** or the cold head **114**. The housing **106** can have a non-reflective inner surface.

The optical detection system **100** can further include a downhole unit **116** (e.g., a downhole tool or a downhole sensor) configured to provide an optical signal over the fiber optic cable **104**. The optical signal can be a pulsed signal originating from distributed sensing, or a continuous signal, among other signals.

The optical detection system **100** can include more than one optical detector **102** (shown within the dashed box in FIG. 1). At least one optical detector **102** can detect light received through the fiber optic cable **104** from more than one downhole unit **116**. The optical detection system **100** can include optical detectors **102** of more than one type. For example, some optical detectors **102** in the optical detection system **100** can be SPDs, avalanche photodiodes, integrated optical chips, etc. Some optical detectors **102** can be non-LLD detectors, or non-ELLD detectors (e.g., other than non-SPD detectors). Non-LLD detectors can include p-i-n (or PIN) photodiodes, phototransistors, photovoltaics, photoconductors. Downhole units **116** can include units configured to detect temperature. Other downhole units **116** can be coupled to the same optical detector **102** or to a group of optical detectors **102**, or in any other configuration. Downhole units **116** can detect other properties and perform other functions such as acoustic sensing, resistivity measurements, etc. Some optical detectors **102** may not be mounted on any cooling mechanism **112**, some optical detectors **102** may be mounted with other optical detectors **102** on a same cooling mechanism **112**, or the optical detection system **100** can include more than one cooling mechanism **112** arranged in any configuration with one or more optical detectors mounted thereto.

As shown in FIG. 4, an optical detection system **400** can further include a switching or splitting mechanism **402** to direct optical signals to an optical detector **404**, **406** based on wavelength of the optical signal, power of the optical signal, polarization, or any other parameter or criterion. For example, high-power optical signals **403** can be routed to non-SPD optical detectors **404**, and away from SPDs **406** and low-powered optical signals **405** can be routed to SPD optical detectors **406**. This routing can be performed to prevent damage to SPD optical detectors **406** while still taking full advantage of LLD and ELLD capabilities of SPD optical detectors **406**. As will be appreciated, high-power optical signals **403** can cause saturation in SPDs **406**, leading to damage to the SPDs **406** or to inaccurate results. In some examples, saturation of SPDs **406** can occur with optical signal inputs having a power of about 100 microwatts, and damage can occur at about 10 milliwatts. The noise floor that can be detected by the SPD **406** can be at a level slightly below saturation level but is typically at least 20-30 dB. The saturation level and noise floors for non-SPD optical detectors **404** may be different from the

5

saturation level and noise floors for SPDs 406. The saturation levels and noise floors also may or may not overlap, and thus multiple types of detectors may be used that can cover the full power range required for system measurement. For at least these reasons, to measure a larger range of possible optical signals, SPD optical detectors 102 are used in a system with non-SPD optical detectors 102. Splitting mechanisms 402 can direct or reroute optical signals based on power level or other criteria, to take advantage of the different power ranges measurable by SPD optical detectors 102 versus non-SPD optical detectors 102.

In addition to or instead of a splitting mechanism 402, the optical detection system 100 can include a coupling mechanism or other mechanism to split the light with optical couplers (with or without feedback). These mechanisms can be multi-stage (e.g., the light can be split in one stage, then split again in a second stage), and can split light based on power, wavelength, or phase. Processor or computation-based systems can also be used in some embodiments to dynamically direct or reroute light signals among any available optical path as power increases, or based on any other criteria.

Referring again to FIG. 1, the optical detection system 100 can further include a measuring device 118 (which may be part of a computer workstation) coupled to the optical detector 102 to obtain measurement data, with a display 120 to display a graphical representation of the measurement data. In some embodiments, some portions of the optical detection system 100 can be positioned at a surface of the Earth, while some portions to the optical detection system 100 can be placed downhole. When more than one optical detector 102 is used, for example, some of the optical detectors 102 can be placed downhole, and some can be placed at the surface. In some embodiments, one or more cooling mechanisms 112 can be placed downhole proximate one or more optical detectors 102 although power and geometry considerations should be taken into account with such configurations to provide power for cooling in an appropriately sized borehole. In some embodiments, the measuring device 118 and display 120 will be situated at the surface of the Earth, for example as shown in FIGS. 6 and 7 described later herein.

FIG. 5 is a flow chart of an example method 500 of optical sensing in accordance with some embodiments. The example method 500 can be performed by the optical detection system 100 (FIG. 1) or by components thereof. The example method 500 begins with operation 502 with coupling an optical sensing apparatus to a downhole unit 116 (e.g., a downhole sensing device) through a fiber optic cable 104. The optical sensing apparatus can include at least one optical detector 102 within a housing 106. However, embodiments are not limited to one optical detector 102. The optical detector 102 can be cooled to a temperature below 210 degrees Kelvin by a cooling mechanism 112. In some embodiments, the optical detector 102 can be cooled to a temperature below 5 degrees Kelvin.

The example method 500 continues with operation 504 with the optical detector 102 receiving optical signals from the downhole sensing device over the fiber optic cable 104. In some embodiments, the downhole sensing device includes an intrinsic fiber optic sensor. In other embodiments, the downhole sensing device comprises at least one fiber Bragg grating or some other reflector. In at least these embodiments, the example method 500 can further include providing an optical signal to the intrinsic fiber optic sensor and receiving a reflected or backscattered optical signal, responsive to providing the optical signal, that represents at

6

least one downhole property. In embodiments, the backscattered signal can include Stokes and anti-Stokes components, or Raleigh components.

In embodiments, many optical signals can be multiplexed onto the fiber optic cable 104. In at least these embodiments, the example method 500 can further include de-multiplexing the optical signals at a switching mechanism, and providing the de-multiplexed signals on at least two separate paths to at least two separate optical detectors 102.

The example method 500 continues with operation 506 with the optical detection system 100 detecting at least one downhole property based on the optical signals. For example, the optical signal can be used to detect different properties of downhole structures, to provide optical analysis of fluid and material composition in a borehole or annulus, to perform geosteering, to determine values for porosity or composition of the borehole wall, etc.

FIG. 6 is a diagram of a wireline system 600 embodiment. The wireline system 600 can comprise portions of a wireline logging tool body 602 as part of a wireline logging operation. Thus, FIG. 6 shows a well during wireline logging operations. In this case, a drilling platform 604 is equipped with a derrick 606 that supports a hoist 608.

Drilling oil and gas wells is commonly carried out using a string of drill pipes connected together so as to form a drilling string that is lowered through a rotary table 610 into a wellbore or borehole 612. Here it is assumed that the drilling string has been temporarily removed from the borehole 612 to allow a wireline logging tool body 602, such as a probe or sonde, to be lowered by wireline or logging cable 614 into the borehole 612. Typically, the wireline logging tool body 602 is lowered to the bottom of the region of interest and subsequently pulled upward at a substantially constant speed.

During the upward trip, at a series of depths instruments (e.g., downhole units 116 described above with reference to FIG. 1) included in the wireline logging tool body 602 can be used to perform measurements on the subsurface geological formations adjacent the borehole 612 (and the wireline logging tool body 602). The measurement data can be communicated to a surface logging facility 616 for storage, processing, and analysis. The logging facility 616 can be provided with electronic equipment for various types of signal processing, which can be implemented by any one or more of the components of the optical detection system 100 (FIG. 1). Similar formation evaluation data can be gathered and analyzed during drilling operations (e.g., during LWD operations, and by extension, sampling while drilling).

The wireline logging tool body 602 is suspended in the wellbore by a wireline cable 614 that connects the tool to a surface control unit (e.g., comprising a measuring device 118 (which can include a workstation and have a corresponding display 120). This wireline cable 614 can include (or perform functionalities of) the fiber optic cable 104 (FIG. 1). The tool can be deployed in the borehole 612 on coiled tubing, jointed drill pipe, hard wired drill pipe, or any other suitable deployment technique.

In addition to wireline embodiments, example embodiments can also be implemented in drilling rig systems. FIG. 7 illustrates a drilling rig system 700 embodiment. The system 700 can include a downhole unit 116 as part of a downhole drilling operation.

Referring to FIG. 7, it can be seen how a system 700 can also form a portion of a drilling rig 702 located at the surface 704 of a well 706. The drilling rig 702 can provide support for a drill string 708. The drill string 708 can operate to penetrate the rotary table 610 for drilling the borehole 612

through the subsurface formations **714**. The drill string **708** can include a Kelly **716**, drill pipe **718**, and a bottom hole assembly **720**, perhaps located at the lower portion of the drill pipe **718**.

The bottom hole assembly **720** can include drill collars **722**, a downhole tool **724**, and a drill bit **726**. The drill bit **726** can operate to create the borehole **612** by penetrating the surface **704** and the subsurface formations **615**. The downhole tool **724** can comprise any of a number of different types of tools including MWD tools, LWD tools, and others. The downhole tool can communicate with the logging facility **616**. In some examples, fiber optic cable **104** will be spliced, rerouted, coupled, guided, or otherwise modified to maintain connections at each drill collar **722** and at each position along the drill string **708**. In some embodiments, a fiber optic connector can be provided at each drill collar **722** or other joint or position downhole. In some embodiments, the fiber optic cable **104** can be placed inside a steel casing **725** as shown in FIG. 7, outside the casing **725** (as shown in FIG. 8 and described below), inside or outside of a production tube, inside or outside of coiled tubing, on a wireline cable, or in any other placement, configuration, or combination thereof. In some embodiments, downhole units **116** can be placed in a repeater configuration or in an amplifier configuration to improve signal strength at the surface. In yet other embodiments, fiber can be deployed continuously through a drill string using a dart, a torpedo, a reel, a feedthrough, or some other deployment device.

During drilling operations, the drill string **708** (perhaps including the Kelly **716**, the drill pipe **718**, and the bottom hole assembly **720**) can be rotated by the rotary table **610**. Although not shown, in addition to, or alternatively, the bottom hole assembly **720** can also be rotated by a motor (e.g., a mud motor) that is located downhole. The drill collars **722** can be used to add weight to the drill bit **726**. The drill collars **722** can also operate to stiffen the bottom hole assembly **720**, allowing the bottom hole assembly **720** to transfer the added weight to the drill bit **726**, and in turn, to assist the drill bit **726** in penetrating the surface **704** and subsurface formations **714**.

Thus, it can be seen that in some embodiments, the systems **600**, **700** can include a drill collar **722**, a downhole tool **724**, and/or a wireline logging tool body **602** to house one or more downhole units, similar to or identical to the downhole units **116** providing information over the fiber optic cable **104** and illustrated in FIGS. 1 and 2.

Thus, for the purposes of this document, the term “housing” when used to address tools below the surface (e.g., downhole), can include any one or more of a drill collar **722**, a downhole tool **724**, or a wireline logging tool body **602** (all having an outer wall, to enclose or attach to magnetometers, sensors, fluid sampling devices, pressure measurement devices, transmitters, receivers, acquisition and processing logic, and data acquisition systems). The tool **724** can comprise a downhole tool, such as an LWD tool or MWD tool. The wireline logging tool body **602** can comprise a wireline logging tool, including a probe or sonde, for example, coupled to a logging cable **614**. Many embodiments can thus be realized.

Thus, a system **600**, **700** can comprise a downhole tool body, such as a wireline logging tool body **602** or a downhole tool **724** (e.g., an LWD or MWD tool body), and fiber optic cable **104** to provide signaling to the optical detection system **100** or to components thereof (e.g., an optical detector **102**) as described above.

The physical structure of such instructions can be operated on by one or more processors. Executing instructions

determined by these physical structures can cause the optical detection system **100** or components thereof to perform operations according to methods described herein. The instructions can include instructions to cause associated data or other data to be stored in a memory.

The wireline logging tool body **602** (FIG. 6) can include or otherwise be utilized in conjunction with any number of measurement tools such as resistivity tools, seismic tools, acoustic tools, temperature sensors, porosity sensors and others. In one embodiment, the wireline logging tool body **602** is equipped with transmission equipment to communicate ultimately to a surface processing unit of a surface logging facility **616** (FIG. 6). Such transmission equipment can take any desired form, and different transmission media and methods can be used. Examples of connections include wired, fiber optic, wireless connections and memory based systems.

FIG. 8 is a diagram of a permanent monitoring system embodiment. In the system **800**, cement **802** fills an annulus **804** formed radially between casing **723** and a borehole **612**.

As used herein, the term “cement” is used to indicate a hardenable material which is used to seal off an annular space in a well, such as the annulus **804**. Cement is not necessarily cementitious, and other types of materials (e.g., polymers, such as epoxies, etc.) can be used in place of, or in addition to, a Portland type of cement. Cement can harden by hydrating, by passage of time, by application of heat, by cross-linking, and/or by any other technique.

As used herein, herein, the term “casing” is used to indicate a generally tubular string that forms a protective wellbore lining. Casing may include any of the types of materials known to those skilled in the art as casing, liner or tubing. Casing may be segmented or continuous, and may be supplied ready for installation, or may be formed in situ.

Conditions of cement, or any other downhole condition, can be monitored using the permanent monitoring system **800**. One or more fiber optic cables **104** can be disposed in the well, so that they are operative to sense certain parameters in the well, for example properties of the cement **802**. As depicted in FIG. 8, the fiber optic cable **104** is positioned in the annulus **804** between the casing **723** and the borehole **612**, but in other examples the fiber optic cable **104** could be positioned in a wall of the casing, or adjacent the formation **714**.

The fiber optic cable **104** can be strapped, clamped, or otherwise secured to an exterior of the casing **723**. The system **800** further includes components of the system **100** (FIG. 1) for example optical detection apparatus **101**, measuring device **118** or any other component of the system **100**. Accordingly, the system **800** can monitor downhole conditions for months or even years after well completion.

Additional Embodiments

As mentioned earlier herein with respect to FIG. 1, optical detectors **102** in the optical detection system **100** (FIG. 1) can be SPDs. These SPDs can detect very low levels of light found in many photonics-based applications. Low light levels may, in some limit the ability to conduct downhole sensing operations. For example, some systems have losses of up to 110 dB, which limits the range, data rate, or the resolution of operation of optical detection systems. As further described earlier herein, the SNR in some systems can be reduced due to the presence of noise sources, including thermal noise and other noise. Some embodiments provide optical detection systems that use SPDs to enhance or increase SNRs by removing noise sources and reducing

signal loss. Some embodiments also provide more robust data detection for enhanced sensing.

SPDs, such as superconducting nanowire SPDs (SNSPDs), operate by detecting a quantum state disturbance by an incoming photon incident on the corresponding optical detector **102**. By combining the use of SPD-type optical detector **102** at the surface with downhole units **116**, very low-energy signals (e.g., at the energy of a single photon) can be detected. In addition, SNSPD-type optical detectors **102** can provide efficient operation at a wide range of wavelengths (e.g., from ultra-violet to mid-infrared wavelength regions), low dark counts (due to the removal of thermal noise from the optical detection system **100**), short recovery periods (e.g., recovery periods on the order of 1-10 nanoseconds), and low timing jitter (e.g., timing jitter on the order of 100-500 picoseconds). SPD-type optical detectors **102** can be integrated into closed-cycle refrigerator-based detector systems, allowing for advanced photon counting in oil and gas exploration operations that rely on portability and durability in fielded detection devices and systems.

SPDs can operate over wavelengths of 100-200 nm centered around a center frequency that depends on the fabrication of the SPD. By changing parameters of the fabrication (e.g., the timing or duration of etching or the thickness of a nanowire layer, substrate, or other thickness), the center frequency can be constructed to span wavelengths between ultraviolet wavelengths to mid/far infrared (~200 nm to ~10 micron). Once fabricated though, the SNSPD device spans up to ~200 nm. Accordingly, to detect wavelengths covering a range of, e.g., 200 nm to 10,000 nm, an optical detection apparatus should include 50 SPDs with center frequencies separated by 200 nm.

FIG. 9 a block diagram of an optical detection system **900** including an SPD in accordance with various embodiments. An optical detection apparatus **904** includes an optical detector (e.g., an SNSPD) **902** for detecting light received at an input section **906** of fiber optic cable **908**. The optical detection apparatus **904** can further include a housing **910** for enclosing the optical detector **902** and optically shielding the optical detector **902**. In some embodiments, the input section **906** of fiber optic cable can pass through a housing aperture to permit passage of the fiber optic cable **908**. However, embodiments are not limited thereto, and in some embodiments, a coupler can be mounted so that the fiber optic cable **908** terminates at a boundary of the housing **910**.

Similarly to the optical detection system **100** (FIG. 1), the optical detection system **900** includes a light source **912**, separate from the optical detector **902** and the housing **910**, for providing light through the fiber optic cable **908** to a downhole sensing unit **914**. The light source **912** may be provided at a surface of the Earth, for example.

The optical detection system **900** further includes a cryogenic cooler **916** to remove heat to maintain the temperature of a light-sensitive region of the optical detector **902** within a superconducting temperature range of the optical detector **902**. As described above regarding the cooling mechanism **112** (FIG. 1), in some embodiments, the cryogenic cooler **916** operates using one of liquid helium (He) and liquid nitrogen (N₂), to reach temperatures ranging down to about 77 K or about 2.5 K. The cryogenic cooler **916** can operate in a closed-loop system with a few hundred watts (e.g., 100-200 watts) of power, and has low servicing and replenishment specifications, which enables portable and low-risk use in oil and gas operations. As described above, the cryogenic cooler **916** can be of one or more of a variety of configurations, including Dilution-Magnetic, Collins-Helium Liquefier, Joule-Thomson, Stirling-cycle cryocooler,

self-regulated Joule-Thomson, Closed-Cycle Split-Type Stirling, Pulse Tube, a two-stage Gifford-McMahon cryogenic cooler or multi-stage Gifford-McMahon cryogenic cooler, or a cooler using magnetocaloric effect, by way of example.

Similarly to the optical detection system **100** (FIG. 1), the optical detection system **900** can further include multiple optical detectors, which can be SPD optical detectors, SNSPD optical detectors, or other types of non-SPD optical detectors. An SPD optical detector **902** can detect light within a first dynamic range while non-SPD optical detectors can detect levels of light having a dynamic range distinct, but not necessarily exclusive, of the first dynamic range.

An SNSPD for use in various embodiments can be configured to include a superconductive meandering nanowire structure. FIG. 10A illustrates an SNSPD **1000** using meandering nanowires **1002** in accordance with various embodiments. FIG. 10B illustrates an enlarged view of the SNSPD **1000** of FIG. 10A. The SNSPD **1000** of FIGS. 10A and 10B can include niobium nitride nanowires grown on magnesium oxide or sapphire substrates, although embodiments are not limited to any particular substrate material or nanowire material. For example, the nanowires **1002** can also include tungsten silicide, niobium silicide, and tantalum nitride. The nanowires **1002** meander between bonding pads **1004** in a compact meander geometry to create a square or circular pixel with high detection efficiency. Embodiments are not limited to a meandering nanowire **1002**. For example, the nanowires **1002** can be configured in a superconductive interleaved nanowire structure, and/or nanowires **1002** can be parallel to each other.

The dimensions (e.g., diameter, length, etc.) of the nanowires **1002** are chosen such that a uniform optical cavity, optimized for the specific wavelength of the produced light, is provided along the length of nanowire. The nanowires **1002** can be fabricated such that the diameter of the nanowire **1002** is sufficiently wide to capture the desired light. For example, the diameter of the nanowire **1002** should be larger than $\lambda/2n_w$, wherein λ is the wavelength of the desired light and n_w is the refractive index of the nanowire. For example, nanowires **1002** used in various embodiments can have diameters of about 90-100 nanometers or less, or to a few hundred nanometers.

Some embodiments provide a reflective layer or a cavity on the substrate that extends under the nanowire **1002**. The reflective layer can reflect light that is guided by the nanowire **1002**. The reflective layer can be provided in the form of a multilayered structure comprising repeated layers of silicates for example, or as a metal film to provide further system efficiencies due to light or photon reflection that allows the nanowire a second chance to detect a given photon or photons. Some embodiments can include many layers (e.g., three to five layers, or more) of photonic crystals (e.g., Ta₂O₅ or SiO₂),

Referring again to FIG. 9, a cooling mechanism (e.g., cryogenic cooler **916** (or a cooling mechanism **112** (FIG. 1) or a cooling mechanism **312** (FIG. 3)) can be used to cool a nanowire of the optical detector **902** below the nanowire superconducting critical temperature. A power source **918** provides the optical detector **902** with current. A photon incident on a nanowire of the optical detector **902** breaks Cooper pairs and creates a localized non-superconducting region, or hotspot, with finite electrical resistance on the nanowire. A monitoring unit **920** coupled to an output **922** of the optical detector **902** has an impedance lower than an impedance of a non-superconducting region of the optical

11

detector **902** so that current is shunted to the monitoring unit **920**, resulting in a measurable voltage at the monitoring unit **920**. When the current is shunted from the optical detector **902**, the non-superconducting region of the optical detector **902** can then be re-cooled below a superconducting critical temperature. The monitoring unit **920** detects that a signal has been received at the optical detector **902** and the monitoring unit **920** can provide the signal, or notification of the signal, for further processing. The monitoring unit **920** can be included as a component of the system **600**, **700**, **800** (FIG. 6, FIG. 7, and FIG. 8 respectively) for display or any other use in determining properties of a downhole formation. The monitoring unit **920** can also include, or be coupled to other components that include, a timing unit and a counting unit to determine when photons hit the optical detector **902**, and how many photons hit the optical detector **902**. A timing unit **921** can provide a time stamp. The monitoring unit **920** can also provide a counter to count the photons in reflected measurement signal or other signal.

In some embodiments, an SNSPD-type optical detector **902** includes multiple superconducting nanowire structures. FIG. 11 illustrates an SNSPD having multiple superconducting nanowire structures **1102**, **1104**, **1106**, **1108**, **1110**, **1114**, **1116**, **1118** arranged in parallel in accordance with various embodiments. In some embodiments, the multiple superconducting nanowire structures **1102**, **1104**, **1106**, **1108**, **1110**, **1114**, **1116**, **1118** share a common ground **1120**, or groups of multiple superconducting nanowire structures share a common ground. In some embodiments, the common ground is on a second surface of the magnesium oxide substrate (or other type of substrate) opposing the first surface of the magnesium oxide substrate on which the superconducting nanowire structures **1102**, **1104**, **1106**, **1108**, **1110**, **1114**, **1116**, **1118** are grown. In some embodiments, at least two of the multiple superconducting nanowire structures have separate power sources. In some embodiments, the multiple superconducting nanowire structures **1102**, **1104**, **1106**, **1108**, **1110**, **1114**, **1116**, **1118** share are each configured to measure one signal (e.g., a Stokes signal or an anti-Stokes signal, as described in more detail below). In another array of pixels, on the same chip but in a different location on the chip in some embodiments, superconducting nanowire structures will measure the Stokes or anti-Stokes signal that is the counterpart of the Stokes or anti-Stokes signal measured by the multiple superconducting nanowire structures **1102**, **1104**, **1106**, **1108**, **1110**, **1114**, **1116**, **1118**.

Referring again to FIG. 9, by adjusting or adapting the width and pitch of the nanowire/s during fabrication of the optical detector **902**, the optical detector **902** can be made more efficient. In a 100% efficient SPD-type optical detector **902**, a signal is produced every time a single photon enters optical detector **902**. However, photons can arrive at the optical detector **902** at different polarizations (among other variations). SNSPDs (in contrast to other types of optical detectors) are sensitive to the polarization of light due to the usage of nanowires in their construction, because nanowires are relatively straight along their length, and thus nanowires detect fields that align with the nanowire along its length.

Multilayer SNSPD constructions can overcome these and other challenges to provide improved efficiency. For example, as illustrated in FIG. 12, two or more layers **1202** and **1204** can be vertical stacked and connected in parallel (with a common power source, common ground, etc.) to form a multilayer SNSPD **1200**. Each layer **1202**, **1204** can have nanowires **1206**, **1208** meandering in different patterns, or oriented at orthogonal angles with respect to one another, so that reduced absorptance of light **1210** incident on the

12

SNSPD **1200** at one layer **1202**, **1204** will be offset or adjusted for by absorptance variations at the other layer **1202**, **1204**. By using multiple layers of nanowires **1206**, **1208** with different pitches and patterns, polarization sensitivity can be reduced and the efficiency of the optical detector **902** (FIG. 9) can be enhanced or improved. Additionally, or in the alternative, some embodiments provide multiple layers, each layer detecting a different wavelength or range of wavelengths, so that the optical detector **902** can detect a larger range of wavelengths.

As with other embodiments discussed earlier herein with respect to FIGS. 1-5, the optical detector **902** can be used in a variety of optical systems, including various types of sensor systems. In sensor-based applications, use of SPD-type optical detectors can improve the resolution or deployable distance of distributed acoustic sensing (DAS) systems, distributed temperature sensing (DTS) systems, distributed strain systems (DSS), and distributed chemical sensing systems, etc. Use of SPD-type optical detectors can also allow for high transmission loss interconnects, enabling offshore monitoring. Optical detection systems that use SPD-type optical detectors can be used in systems including many low transmission loss interconnects, for example drill strings that have an interconnect, and some transmission loss, at every joint. Furthermore, optical detection systems that make use of SPD-type optical detectors can detect visible light, and therefore such systems can find extended usage in spectroscopy applications, in rubidium-based gyroscopes, and in rubidium-based magnetometers in on-shore and offshore drilling and oil exploration applications. Optical detection systems that make use of SPD-type optical detectors can detect very weak signals (e.g., light signals of one photon can be detected), and therefore these optical detection systems can perform operations to operational depths of 35,000 feet or more. Such systems can also operate with minimal or no downhole electronics, leading to cost savings for operators.

FIG. 13 is a flow chart of an example method **1300** of optical sensing using an SNSPD optical detector in accordance with some embodiments. The example method **1300** can be performed by the optical detection system **900** (FIG. 9) or by components thereof. The example method **1300** begins at operation **1302** by coupling an optical detection apparatus **904** to a downhole sensing unit **914** through a fiber optic cable **908**. The optical detection apparatus **904** includes at least one SNSPD-type optical detector **902**.

The example method **1300** continues with operation **1304** with the cryogenic cooler **916** maintaining the temperature of the SNSPD-type optical detector **902** within a superconducting range of the SNSPD-type optical detector **902**.

The example method **1300** continues with operation **1306** with the power source **918** providing current to the SNSPD-type optical detector **902**.

The example method **1300** continues with operation **1308** with detecting an optical signal at the optical detection apparatus **904** upon the monitoring unit **920** measuring a voltage proportional to the superconducting critical current of the SNSPD-type optical detector **902**. The voltage will be generated when photons received at the SNSPD-type optical detector **902** raise the temperature of the SNSPD-type optical detector **902** above the superconducting range of the SNSPD-type optical detector **902** to create an electrical impedance in the SNSPD-type optical detector **902**. The optical signal can be time-correlated to determine how many photons were detected in a certain time period. Other operations can include counting the number of photons

received during a time period to provide a photon count and detecting a downhole property based on the photon count.

In some embodiments in which the optical detection apparatus **904** further includes at least one optical detector **902** that is not an SNSPD or SPD, the example method **1300** further includes directing optical signals having a power level greater than a threshold power level to the at least one optical detector that is not an SPD or SNSPD. In embodiments in which the downhole sensing unit **914** includes an intrinsic fiber optic sensor, the example method **1300** can include providing an optical signal to the intrinsic fiber optic sensor; and receiving a reflected optical signal, responsive to providing the optical signal, that represents at least one downhole property.

Arrayed DAS Using Single-Photon Detectors

As mentioned earlier herein with respect to FIGS. **1-2**, optical detectors **102** can include groups of optical detectors **204** (FIG. **2**) dedicated to DAS. DAS operates using back-scattered Rayleigh signals. However, Rayleigh signals can experience significant loss in intensity before reaching surface systems and, accordingly, DAS operations may be limited in resolution, length of operation, and signal quality.

Furthermore, DAS systems can be costly in that they make use of dedicated laser systems and optical receivers. Embodiments provide apparatuses and methods that use fewer laser sources and fewer arrayed SPDs (e.g., one source and one SPD) to operate more than one DAS system simultaneously. Furthermore, embodiments provide for arrayed SPDs to be arranged to form on-chip balanced photodetectors for improved speed in operation and reduction in DAS system cost.

FIG. **14** is a block diagram of an arrayed DAS system **1400** in accordance with various embodiments. A single laser pulse is generated by a source **1402** and passes through optics (e.g., variable attenuators, pump filters, erbium doped fiber amplifiers, couplers, and other optical devices) **1404**. The source **1402** and optics **1404** can be housed in a surface system, for example, the source **1402** and optics **1404** can be collocated with the measuring device **118** and display **120** (FIGS. **6**, **7** and **8**). The laser pulse is separated onto one path **1406**, **1410**, **1414**, **1418** for each DAS system **1408**, **1412**, **1416**, and **1420**, where a DAS system **1408**, **1412**, **1416**, **1420** includes a fiber optic cable **1424**, **1426**, **1428**, **1430**, a circulator **1442**, **1444**, **1446**, **1448** and optics **1432**, **1434**, **1436**, **1438**. Because the SPD array **1422** can detect faint signals (e.g., signals consisting of as few as one photon), a single source **2402** can have its power divided among several light paths (by a division circuit, splitter, or other circuitry) and still allow operation of DAS systems according to operational requirements. Furthermore, the use of signals with lower power levels allow the laser pulse produced by the source **1402** to maintain linearity during propagation, reducing nonlinear effects, such as self-phase modulation, cross-phase modulation, four-wave mixing, or exponential growth of the backscattering signal. Additionally, two laser sources **1302** at different wavelengths can be used as well.

In embodiments, light (e.g., a “measurement signal”) provided by the source **1402** travels through circulators **1442**, **1444**, **1446** and **1448** to each fiber optic cable **1424**, **1426**, **1428** and **1430** (also shown in FIG. **7**) being used for DAS. Each fiber optic cable **1424**, **1426**, **1428** and **1430** can include at least one sensing location. The sensing locations generate reflected measurement signals (e.g., backscattered Rayleigh signals) representative of measurement parameters

at corresponding positions downhole. In some embodiments, the sensing locations can be locations of spontaneous Rayleigh scattering. The backscattered Rayleigh signal/s return through conditioning optics circuitry **1432**, **1434**, **1436** and **1438** (such as, e.g., wavelength demultiplexers, couplers, or optical filters) before being detected by the SPD array **1422**. The backscattered Rayleigh signal/s are typically at about the same optical frequency as the light provided by the source **1402**. As shown in FIGS. **6** and **7**, the SPD array **1422** can be located in a surface system; for example, the SPD array **1422** can be collocated with the measuring device **118** and the display **120**.

In embodiments, the fiber optic cables **1424**, **1426**, **1428** and **1430** can be shared with DTS systems. DTS systems use inelastic (Raman) scattering rather than the elastic (Rayleigh) scattering being employed by DAS systems. As DTS is often performed at a shorter wavelength than DAS (e.g., 1064 nm versus 1550 nm), a DAS system and DTS system can operate in parallel without causing optical interference. A wavelength division multiplexer can be provided to couple light sources for both DTS and DAS to the sensing fiber. If some loss is acceptable, the multiplexer can be replaced with a beam splitter.

The SPD array **1422** can be matched so that one element of the SPD array **1422** detects one signal and a second element detects a different signal. The use of matched detectors can enable improved use of available light and can cancel light common to both outputs, in particular common-mode noise. The SPD array **1422** outputs can be compared in a balanced receiver **1439** configuration (using either external electronic circuitry or an on-chip integrated system, for example, as described in more detail below with reference to FIG. **16**) to retrieve phase information for any or all of the light signals. In some examples, the phase information includes in-phase (I) or quadrature (Q) phase information. Processing circuitry **1440** can then produce an acoustic signal representative of a downhole property based on the phase information (e.g., the I/Q phase information) of the backscattered Rayleigh signal using methodologies and algorithms as described later herein.

FIG. **15A** illustrates an example SPD array **1422** for fiber imaging in accordance with various embodiments. Arrays of SNSPDs (e.g., “pixels”) **1502** can be used to provide DAS under low-light (e.g., “photon starved”) conditions. The array **1422** shown in FIG. **15A** includes 64 pixels **1502**. In comparing FIG. **15A** with FIG. **11**, it will be appreciated that each of nanowire structures **1102**, **1104**, **1106**, **1108**, **1110**, **1114**, **1116**, **1118** correspond to pixels **1502**. The pixels **1502** can be fabricated on a silicon substrate with a thermally-oxidized silicon oxide layer or on single-crystal MgO, although embodiments are not limited thereto. Interconnection lines **1504** can be formed in the spaces between pixels **1502** and these interconnection lines can be connected to coplanar waveguide lines **1506**. By creating a regular pattern over a large number of pixels (e.g., 64-100 pixels, though as few as two pixels can be used, or more than 100 pixels can be used), operators can gain information about the spatial distribution of the incoming stream of photons.

FIG. **15B** illustrates an example grid **1510** of multiple SNSPD arrays **1512**. Each of the multiple SNSPD arrays **1512** can couple to at least one fiber optic cable **1424**, **1426**, **1428**, **1430** (FIG. **14**, not shown in FIG. **15B**). In some embodiments, the grid **1510** will be comprised of a square number of SNSPD arrays **1512**, for example, the grid **1510** can comprise fifteen SNSPD arrays **1512** in one row **1514** of the grid **1510** and fifteen columns **1516** of SNSPD arrays **1512**. The number of SNSPD arrays **1512** can be selected

15

based on known, detected or predicted properties of the backscattered Rayleigh signals, for example, the number of SNSPD arrays **1512** can be selected based on power, wavelength, polarization, etc. of the backscattered Rayleigh signals that are expected to be received at the grid **1510**.

FIG. **16** is a block diagram of a balanced receiver **1439** circuitry for retrieving phase information from a backscattered Rayleigh signal in accordance with various embodiments. The balanced receiver **1439** can employ either heterodyne or homodyne coherent detection to extract phase information from the backscattered Rayleigh signal. Description of the balanced receiver **1439** is made with reference to some of the elements of FIG. **14**.

The balanced receiver **1439** includes at least two inputs **1602** and **1604**. One of the inputs (e.g., **1602**) can include the Rayleigh scattering of the probe pulse, wherein the probe pulse was provided by the source **1402** (FIG. **14**).

Generally, if backscattered Rayleigh signals are sent directly to a detector, the phase information is lost and the signal relates purely to the amplitude of the backscattered Rayleigh signal. However, when the backscattered Rayleigh signal is demodulated through mixing with light from a surface source (e.g., a local oscillator (LO) source), then the backscattered Rayleigh signal and the LO source combine to provide a signal that retains phase information of the backscattered Rayleigh signal. Accordingly, in some embodiments, the balanced receiver includes an LO **1612** and at least one of the two inputs **1602** and **1604** can be configured to receive an output of the LO **1612**. Such a system can be referred to as a coherent-detection system.

If the LO **1612** and the backscattered Rayleigh signals are at different frequencies, the system is referred to as a heterodyne system; otherwise the system is referred to as a homodyne system. In homodyne systems, the relative phase of the backscattered Rayleigh signal and LO **1612** signal is zero (it is usually non-zero for heterodyne), so homodyne systems are more phase-sensitive than heterodyne systems. Furthermore, coherent homodyne detection methods and systems include at least one fewer mixing stages than heterodyne methods and systems, thus adding lower noise during the demodulation process, compared with heterodyne demodulation. Heterodyne detection, however, allows flexibility in changing the optical carrier frequency if the receiver is not co-located with the transmitter.

The inputs **1602** and **1604** can be split into two beams by splitters **1606** and **1608** to provide polarization components **1610** of the backscattered Rayleigh signal and polarization components **1612** of the LO signal. The balanced receiver **1439** can include 90° optical hybrid mixers **1614** and **1616** to receive the polarization components **1610** of the backscattered Rayleigh signal and polarization components **1612** of the LO signal. These mixers **1614** and **1616** provide I and Q signals allowing determination of the amplitude and phase of the received backscattered Rayleigh signal. The beats between the signal polarization components **1610** and **1612** are detected by photodiodes **1618**, and the resulting photocurrents are amplified and converted to output voltages I_x , Q_x , I_y , and Q_y by linear trans-impedance amplifiers (TIA) **1620**.

Data acquisition circuitry **1622** processes output voltages I_x , Q_x , I_y , and Q_y to determine and track phase at each separate location to generate an acoustic signal. Systems and methods in accordance with various embodiments generate an acoustic signal by first finding the phase $(\phi) = \tan^{-1}(Q/I)$ at each separate location x . For each x , systems find the change in phase with time $(d\phi/dt)$ and then take the Fourier transform to get the acoustic spectrum. The total acoustic

16

power would be the integral of the acoustic spectrum. The acoustic spectrum will be representative of a downhole property and can be processed according to known methods to determine downhole properties. Data acquisition outputs can be provided to the processor **1440** for other processing, for storage in local or remote systems, and for processing for display on a user interface, among other uses. The data acquisition circuitry **1622** can include a suitable processor (e.g., general purpose processor, microcontroller) and associated memory device for performing processing functions, such as normalization of the acquired data, data averaging, data storage, and/or display to a user or operator of the system.

FIG. **17** is a flow chart of an example method **1700** of measuring a downhole property in accordance with various embodiments. The example method **1700** can be performed by the arrayed DAS system **1400** (FIG. **14**), or by components thereof. The example method **1700** begins with operation **1702** with disposing a fiber optic cable (e.g., fiber optic cable/s **1424**, **1426**, **1428** and/or **1430**, FIG. **14**) in a downhole location. The fiber optic cable **1424**, **1426**, **1428** and/or **1430** can include a sensing location configured to generate backscattered Rayleigh signals.

The example method **1700** continues with operation **1704** with the source **1402** transmitting a measurement signal into the fiber optic cable/s **1424**, **1426**, **1428** and/or **1430** from a surface location. The measurement signal can have an energy level less than or equal to a saturation energy level of a superconducting nanowire single-photon detector (SNSPD) coupled to the fiber optic cable/s **1424**, **1426**, **1428** and/or **1430**. The sensing locations generate reflected measurement signals (e.g., backscattered Rayleigh signals). The measurement signal can include light having a wavelength within a visible or infrared range. In embodiments, the source **1402** can provide the measurement signal in pulses of fewer than 100 nanoseconds (and in some embodiments fewer than 5 nanoseconds) in length.

The example method **1700** continues with operation **1706** with circuitry (e.g., data acquisition circuitry **1622**, processor **1440**, etc.) generating an acoustic signal representative of a downhole property based the phase of the backscattered Rayleigh signal. In examples, the circuitry can generate the acoustic signal by interfering (using an interferometer) the backscattered Rayleigh signal with a coherent signal. In some embodiments, the phase includes an I component and a Q component.

In some embodiments, at least one fiber optic cable/s **1424**, **1426**, **1428** and/or **1430** can provide reflected measurement signals (e.g., backscattered Rayleigh signals, or other light signals, etc.) to non-SPD detectors, or to SPD detectors that are not SNSPD detectors (e.g., photomultiplier tubes, avalanche photodiodes, frequency up-conversion detectors, visible light photon counters, transition edge sensors, quantum dots, etc.) The distance between the source and the sensing location can be 100 feet or more. In embodiments, backscattered Rayleigh signals (or any other signals reflected from downhole sensing locations) can be routed based on one or more properties such as polarization, wavelength, and the number of photons in the reflected signal (e.g., in the backscattered Rayleigh signal).

In various embodiments, a non-transitory machine-readable storage device can comprise instructions stored thereon, which, when performed by a machine, cause the machine to perform operations, the operations comprising one or more features similar to or identical to features of methods and techniques described herein. A machine-readable storage device, herein, is a physical device that stores data repre-

sented by physical structure within the device. Examples of machine-readable storage devices can include, but are not limited to, memory in the form of read only memory (ROM), random access memory (RAM), a magnetic disk storage device, an optical storage device, a flash memory, and other electronic, magnetic, or optical memory devices, including combinations thereof. These can be provided in integrated chips that include optical detectors **102**, or in other surface computer systems for taking measurements or analyzing measurements as part of the optical detection system **100**, **300**, **900**, and **1400** (FIGS. **1**, **3**, **9**, and **14**).

Any of the above components, for example components of the optical detection system **100**, **300**, **900**, and **1400**, can all be characterized as “modules” herein. Such modules can include hardware circuitry, and/or a processor and/or memory circuits, software program modules and objects, and/or firmware, and combinations thereof, as desired by the architect of the optical detection system **100** as appropriate for particular implementations of various embodiments. For example, in some embodiments, such modules can be included in an apparatus and/or system operation simulation package, such as a software electrical signal simulation package, a power usage and distribution simulation package, a power/heat dissipation simulation package, and/or a combination of software and hardware used to simulate the operation of various potential embodiments.

It should also be understood that the apparatus and systems of various embodiments can be used in applications other than for logging operations, and thus, various embodiments are not to be so limited. The illustrations of optical detection systems **100**, **300**, **900**, and **1400** are intended to provide a general understanding of the structure of various embodiments, and they are not intended to serve as a complete description of all the elements and features of apparatus and systems that might make use of the structures described herein.

Applications that can include the novel apparatus and systems of various embodiments include electronic circuitry used in high-speed computers, communication and signal processing circuitry, modems, processor modules, embedded processors, data switches, and application-specific modules. Some embodiments include a number of methods.

It should be noted that the methods described herein do not have to be executed in the order described, or in any particular order. Moreover, various activities described with respect to the methods identified herein can be executed in iterative, serial, or parallel fashion. Information, including parameters, commands, operands, and other data, can be sent and received in the form of one or more carrier waves.

Upon reading and comprehending the content of this disclosure, one of ordinary skill in the art will understand the manner in which a software program can be launched from a computer-readable medium in a computer-based system to execute the functions defined in the software program. One of ordinary skill in the art will further understand the various programming languages that can be employed to create one or more software programs designed to implement and perform the methods disclosed herein. For example, the programs can be structured in an object-orientated format using an object-oriented language such as Java or C#. In another example, the programs can be structured in a procedure-orientated format using a procedural language, such as assembly or C. The software components can communicate using any of a number of mechanisms well known to those skilled in the art, such as application program interfaces or interprocess communication techniques, including remote procedure calls. The teachings of various embodi-

ments are not limited to any particular programming language or environment. Thus, other embodiments can be realized.

In summary, using the apparatus, systems, and methods disclosed herein can provide more accurate measurements by optical detection apparatuses through removal or reduction of noise sources including thermal noise sources. These advantages can significantly enhance the value of the services provided by an operation/exploration company, while at the same time controlling time-related costs.

The accompanying drawings that form a part hereof, show by way of illustration, and not of limitation, specific embodiments in which the subject matter can be practiced. The embodiments illustrated are described in sufficient detail to enable those skilled in the art to practice the teachings disclosed herein. Other embodiments can be utilized and derived therefrom, such that structural and logical substitutions and changes can be made without departing from the scope of this disclosure. This Detailed Description, therefore, is not to be taken in a limiting sense, and the scope of various embodiments is defined only by the appended claims, along with the full range of equivalents to which such claims are entitled.

Such embodiments of the inventive subject matter can be referred to herein, individually and/or collectively, by the term “invention” merely for convenience and without intending to voluntarily limit the scope of this application to any single invention or inventive concept if more than one is in fact disclosed. Thus, although specific embodiments have been illustrated and described herein, it should be appreciated that any arrangement calculated to achieve the same purpose can be substituted for the specific embodiments shown. This disclosure is intended to cover any and all adaptations or variations of various embodiments. Combinations of the above embodiments, and other embodiments not specifically described herein, will be apparent to those of skill in the art upon reviewing the above description.

Various examples include:

Example 1 is a system, detection system or other device or apparatus (e.g., an optical detection system), comprising: a fiber optic cable to be disposed in a downhole location, the fiber optic cable including a sensing location to generate a backscattered Rayleigh signal representative of measurement parameters; a light source, at a surface of the Earth, to transmit a measurement signal to cause the sensing location to provide the backscattered Rayleigh signal; an optical detector device comprising at least one single-photon detector (SPD) for detecting the backscattered Rayleigh signal received over the fiber optic cable; and circuitry to produce an acoustic signal representative of a downhole property based on a phase of the backscattered Rayleigh signal.

In Example 2, the subject matter of Example 1 can optionally include wherein the phase includes an in-phase (I) component and quadrature (Q) component.

In Example 3, the subject matter of Example 2 can optionally include wherein the circuitry includes at least two inputs, at least one of the at least two inputs to receive the backscattered Rayleigh signal; mixer circuitry to receive the two inputs; and circuitry to interfere outputs of the mixer circuitry and to determine the I and Q components of the backscattered Rayleigh signal.

In Example 4, the subject matter of Example 3 can optionally include wherein the circuitry includes an oscillator, and wherein at least one of the at least two inputs is configured to receive an output of the oscillator.

In Example 5, the subject matter of Example 2 can optionally include an optical splitter to split the backscattered Rayleigh signal into a plurality of optical paths, and wherein the optical detector includes a plurality of SPDs, the plurality of SPDs being arranged in pairs such that a first SPD of a pair detects a first light signal on a first optical path of the plurality of optical paths, and a second SPD of the pair detects a second light signal on a second optical path of the plurality of paths.

In Example 6, the subject matter of Example 5 can optionally include wherein the plurality of SPDs include superconducting nanowire SPDs (SNSPDs), and wherein the optical detection system further comprises a cryogenic cooler configured to maintain the temperature of light-sensitive regions of the SNSPDs within a superconducting temperature range of the SNSPDs.

In Example 7, the subject matter of Example 6 can optionally include wherein the cryogenic cooler operates using one of liquid helium (He) and liquid nitrogen (N₂).

In Example 8, the subject matter of Example 2 can optionally include a routing circuit to route the backscattered Rayleigh signal to provide at least a second backscattered Rayleigh signal when a count of the number of photons in the backscattered Rayleigh signal reaches or exceeds a threshold number of photons.

In Example 9, the subject matter of Example 2 can optionally include wherein the fiber optic cable includes a plurality of sensing locations along a measurement length of the fiber optic cable, the plurality of sensing locations configured to provide a plurality of backscattered Rayleigh signals representative of values of the measurement parameters at corresponding positions downhole.

In Example 10, the subject matter of Example 9 can optionally include wherein the plurality of sensing locations are locations of spontaneous Rayleigh scattering.

In Example 11, the subject matter of Example 2 can optionally include wherein the plurality of SPDs share a common ground.

In Example 12, the subject matter of Example 2 can optionally include wherein the fiber optic cable is configured for use as a distributed acoustic sensing (DAS) fiber/

In Example 13, the subject matter of Example 12 can optionally include a plurality of fiber optic cables, each of the plurality of fiber optic cables configured to operate as a DAS fiber.

In Example 14, the subject matter of Example 2 can optionally include a monitoring unit coupled to an output of the SNSPD, the monitoring unit having an impedance lower than an impedance of a non-superconducting region of the SNSPD, the monitoring unit configured to provide measurement data of the SNSPD; and a display to display a graphical representation of the measurement data.

In Example 15, the subject matter of Example 2 can optionally include wherein the light source is configured to transmit a measurement signal having an energy level below a threshold energy level such that each backscattered Rayleigh signal has an energy below a saturation energy level of each of the plurality of SPDs.

In Example 16, the subject matter of Example 2 can optionally include a housing for enclosing the optical detector and to optically shield the optical detector, the housing including an aperture for passage of the fiber optic cable.

Example 17 is a method for estimating a downhole property, the method comprising: disposing a fiber optic cable in a downhole location, the fiber optic cable including a sensing location configured to generate backscattered Rayleigh signals; transmitting a measurement signal into the

fiber optic cable from a surface location, the measurement signal having an energy level less than or equal to a saturation energy level of a superconducting nanowire single-photon detector (SNSPD) coupled to the fiber optic cable, to cause the sensing location to return the backscattered Rayleigh signal to the surface location; and generating an acoustic signal representative of a downhole property based on a phase of the backscattered Rayleigh signal by interfering the backscattered Rayleigh signal with a coherent signal.

In Example 18, the subject matter of Example 17 can optionally include wherein the phase includes an in-phase (I) component and quadrature (Q) component.

In Example 19, the subject matter of Example 18 can optionally include splitting the backscattered Rayleigh signal into a plurality of optical paths; detecting a first light signal on a first optical path of the plurality of optical paths; and detecting a second light signal on a second optical path of the plurality of paths.

In Example 20, the subject matter of Example 18 can optionally include maintaining the temperature of light-sensitive regions of the SNSPDs within a superconducting temperature range of the SNSPDs.

In Example 21, the subject matter of Example 18 can optionally include routing the backscattered Rayleigh signal to provide at least a second backscattered Rayleigh signal based on at least one of polarization, wavelength, and a count of the number of photons in the backscattered Rayleigh signal.

Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that any arrangement that is calculated to achieve the same purpose can be substituted for the specific embodiments shown. Various embodiments use permutations or combinations of embodiments described herein. It is to be understood that the above description is intended to be illustrative, and not restrictive, and that the phraseology or terminology employed herein is for the purpose of description. Combinations of the above embodiments and other embodiments will be apparent to those of ordinary skill in the art upon studying the above description.

What is claimed is:

1. An optical detection system comprising:

a fiber optic cable to be disposed in a downhole location, the fiber optic cable including a sensing location to generate a backscattered Rayleigh signal representative of measurement parameters;

a light source, at a surface of the Earth, to transmit a measurement signal to cause the sensing location to provide the backscattered Rayleigh signal;

an optical detector device comprising at least one single-photon detector (SPD) for detecting the backscattered Rayleigh signal received over the fiber optic cable;

circuitry to produce an acoustic signal representative of a downhole property based on a phase of the backscattered Rayleigh signal,

wherein the phase includes an in-phase (I) component and quadrature (Q) component; and

an optical splitter to split the backscattered Rayleigh signal into a plurality of optical paths, and wherein the optical detector includes a plurality of SPDs, the plurality of SPDs being arranged in pairs such that a first SPD of a pair detects a first light signal on a first optical path of the plurality of optical paths, and a second SPD of the pair detects a second light signal on a second optical path of the plurality of paths.

21

2. The optical detection system of claim 1, wherein the circuitry includes:

at least two inputs, at least one of the at least two inputs to receive the backscattered Rayleigh signal; mixer circuitry to receive the two inputs; and circuitry to interfere outputs of the mixer circuitry and to determine the I and Q components of the backscattered Rayleigh signal.

3. The optical detection system of claim 2, wherein the circuitry includes an oscillator, and wherein at least one of the at least two inputs is configured to receive an output of the oscillator.

4. The optical detection system of claim 1, wherein the plurality of SPDs include superconducting nanowire SPDs (SNSPDs), and wherein the optical detection system further comprises a cryogenic cooler configured to maintain the temperature of light-sensitive regions of the SNSPDs within a superconducting temperature range of the SNSPDs.

5. The optical detection system of claim 4, wherein the cryogenic cooler operates using one of liquid helium (He) and liquid nitrogen (N₂).

6. The optical detection system of claim 1, wherein the fiber optic cable includes a plurality of sensing locations along a measurement length of the fiber optic cable, the plurality of sensing locations configured to provide a plurality of backscattered Rayleigh signals representative of values of the measurement parameters at corresponding positions downhole.

7. The optical detection system of claim 6, wherein the plurality of sensing locations are locations of spontaneous Rayleigh scattering.

8. The optical detection system of claim 1, wherein: the plurality of SPDs share a common ground; or the fiber optic cable is configured for use as a distributed acoustic sensing (DAS) fiber.

9. The optical detection system of claim 8, further comprising a plurality of fiber optic cables, each of the plurality of fiber optic cables configured to operate as a DAS fiber.

10. The optical detection system of claim 1, further comprising:

a housing for enclosing the optical detector and to optically shield the optical detector, the housing including an aperture for passage of the fiber optic cable.

11. A method for measuring a downhole property, the method comprising:

disposing a fiber optic cable in a downhole location, the fiber optic cable including a sensing location configured to generate backscattered Rayleigh signals; transmitting a measurement signal into the fiber optic cable from a surface location, the measurement signal having an energy level less than or equal to a saturation energy level of a superconducting nanowire single-photon detector (SNSPD) coupled to the fiber optic cable, to cause the sensing location to return the backscattered Rayleigh signal to the surface location; and generating an acoustic signal representative of a downhole property based on a phase of the backscattered Rayleigh signal by interfering the backscattered Rayleigh signal with a coherent signal.

12. The method of claim 11, wherein the phase includes an in-phase (I) component and quadrature (Q) component.

13. The method of claim 12, further comprising: splitting the backscattered Rayleigh signal into a plurality of optical paths; detecting a first light signal on a first optical path of the plurality of optical paths; and

22

detecting a second light signal on a second optical path of the plurality of paths.

14. The method of claim 12, further comprising: maintaining the temperature of light-sensitive regions of the SNSPDs within a superconducting temperature range of the SNSPDs.

15. The method of claim 12, further comprising: routing the backscattered Rayleigh signal to provide at least a second backscattered Rayleigh signal based on at least one of polarization, wavelength, and a count of the number of photons in the backscattered Rayleigh signal.

16. An optical detection system comprising: a fiber optic cable to be disposed in a downhole location, the fiber optic cable including a sensing location to generate a backscattered Rayleigh signal representative of measurement parameters; a light source, at a surface of the Earth, to transmit a measurement signal to cause the sensing location to provide the backscattered Rayleigh signal; an optical detector device comprising at least one single-photon detector (SPD) for detecting the backscattered Rayleigh signal received over the fiber optic cable; circuitry to produce an acoustic signal representative of a downhole property based on a phase of the backscattered Rayleigh signal, wherein the phase includes an in-phase (I) component and quadrature (Q) component; and

a routing circuit to route the backscattered Rayleigh signal to provide at least a second backscattered Rayleigh signal when a count of the number of photons in the backscattered Rayleigh signal reaches or exceeds a threshold number of photons.

17. An optical detection system comprising: a fiber optic cable to be disposed in a downhole location, the fiber optic cable including a sensing location to generate a backscattered Rayleigh signal representative of measurement parameters; a light source, at a surface of the Earth, to transmit a measurement signal to cause the sensing location to provide the backscattered Rayleigh signal; an optical detector device comprising at least one single-photon detector (SPD) for detecting the backscattered Rayleigh signal received over the fiber optic cable; circuitry to produce an acoustic signal representative of a downhole property based on a phase of the backscattered Rayleigh signal, wherein the phase includes an in-phase (I) component and quadrature (Q) component; and

a monitoring unit coupled to an output of a superconducting nanowire SPD (SNSPD), the monitoring unit having an impedance lower than an impedance of a non-superconducting region of the SNSPD, the monitoring unit configured to provide measurement data of the SNSPD.

18. An optical detection system comprising: a fiber optic cable to be disposed in a downhole location, the fiber optic cable including a sensing location to generate a backscattered Rayleigh signal representative of measurement parameters; a light source, at a surface of the Earth, to transmit a measurement signal to cause the sensing location to provide the backscattered Rayleigh signal; an optical detector device comprising at least one single-photon detector (SPD) for detecting the backscattered Rayleigh signal received over the fiber optic cable; and

23

circuitry to produce an acoustic signal representative of a downhole property based on a phase of the backscattered Rayleigh signal, wherein the phase includes an in-phase (I) component and quadrature (Q) component, wherein the light source is configured to transmit a 5 measurement signal having an energy level below a threshold energy level such that each backscattered Rayleigh signal has an energy below a saturation energy level of each of the plurality of SPDs.

* * * * *

10

24